WOOD IN AIRCRAFT CONSTRUCTION

PREPARED BY

FOREST PRODUCTS LABORATORY
FOREST SERVICE
U. S. Department of Agriculture

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REPRINTED FROM

AIRCRAFT DESIGN DATA
BUREAU OF CONSTRUCTION AND REPAIR
NAVY DEPARTMENT

WASHINGTON
GOVERNMENT PRINTING OFFICE
1919

AIRCRAFT DESIGN DATA. NOTE NO. 12.

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[Prepared by the Forest Products Laboratory, Forest Service, U. S. Department of Agriculture.]

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MECHANICAL AND PHYSICAL PROPERTIES.

Wood differs from other structural materials in a great many ways, and the maximum efficiency in its use demands a thorough knowledge of the properties of wood and of the factors which influence these properties. In the following general discussion an attempt is made to explain the principal causes for the wide variations found in the strength of wood and to show how these variations may be largely eliminated in any group of material by proper specification and inspection.

VARIABILITY OF THE STRENGTH OF WOOD.

WOOD NON-HOMOGENEOUS.

Wood is exceedingly variable as compared with other structural materials. This variability is due to a number of factors, heretofore not well understood. For that reason any judgment of the strength of a piece was felt to be uncertain. The causes for variations in the properties of wood can now be given and their effects anticipated within reasonable limits.

VARIATION OF STRENGTH WITH LOCALITY OF GROWTH.

In some cases the locality of growth has an influence on the strength of the timber. For example, tests show a marked difference in strength between the Rocky Mountain and coast types of Douglas fir in favor of the coast type.

This influence of locality is usually overestimated. Different stands of the same species grown in the same section of the country may show as great differences as stands grown in widely separated regions, so that as a rule locality of growth can be neglected.

VARIATION OF STRENGTH WITH POSITION IN THE TREE.

In some instances specimens from different parts of the same tree have been found to show considerable difference in strength. In most cases, however, the wood of the highest specific gravity has the best mechanical properties regardless of its position in the tree. Where this is not the case, the toughest or most shock-resistant material is found near the butt. Above a height of 10 or 12 feet variations of mechanical strength correspond to the variations of specific gravity. Some variations with position in cross section or distance from the pith of the tree have been found which could not be entirely accounted for by differences in specific gravity.

VARIATION OF STRENGTH WITH RATE OF GROWTH.

Strength is not definitely proportional to rate of growth, either directly or inversely.

Timber of any species which has grown with exceptional slowness is usually below the average of the species in strength values.

Among many of the hardwood species, material of very rapid growth is usually above the average in strength properties. Notable exceptions to this are found, however, and rapid growth is no assurance of excellence of material unless accompanied by relatively high specific gravity. This is particularly true of ash.

In the coniferous species, material of very rapid growth is very likely to be quite brash and below the average strength.

VARIATION OF STRENGTH WITH AMOUNT OF SUMMER WOOD.

In many species the proportion of summer wood is indicative of the specific gravity, and different proportions of summer wood are usually accompanied by different specific gravities and strength values. However, proportion of summer wood is not a sufficiently accurate indicator of strength to permit its use as the sole criterion for the acceptance or rejection of airplane material. After some practice one should be able, through observation of the proportion of summer wood, to decide whether any particular piece is considerably below, considerably above, or near the required specific gravity. Caution must be observed in applying this to ash, and perhaps to other hardwoods, since rapid-growth ash is sometimes very low in specific gravity in spite of a large proportion of summer wood. In such cases careful examination will show that the summer wood is less dense than usual.

VARIATION OF STRENGTH WITH SPECIFIC GRAVITY.

A piece of clear, sound, straight-grained wood of any species is not necessarily a good stick of timber. To determine the quality of an individual stick by means of mechanical tests is extremely difficult, because the variations in strength of timber due to variations in moisture content, temperature, speed of test, etc., are so great. Furthermore, a test for one strength property does not always indicate what the other properties of the timber are. Without actual and complete tests, the best criterion of the strength properties of any piece of timber is its specific gravity or weight per unit volume, weight being taken when the wood is completely dry and volume when the wood is at some definite condition of seasoning or moisture content. Specific gravity based on oven-dry volume is greater than that based on the volume at any other moisture condition in proportion to the shrinkage which takes place as the moisture is driven out and the wood is reduced to the oven-dry condition.

Accurate determinations made on seven species of wood, including both hardwoods and conifers, showed a range of only about 4½ per cent in the density of the wood substance, or material of which the cell walls is composed. Since the density of wood substance is so nearly constant, it may be said that the specific gravity of a given piece of wood is a measure of the amount of wood substance contained in a unit volume of it. Very careful analyses based on a vast amount of data have shown that wood of high specific gravity has greater strength than that of low specific gravity. Some fairly definite mathematical relations between specific gravity and the various strength properties have been worked out. Some of the strength properties (strength in compression parallel to grain and modulus of elasticity) vary directly as the first power of the specific gravity; others, however, vary with higher powers of the specific gravity, i. e., the strength property changes more rapidly than the specific gravity, a 10 per cent increase of specific gravity resulting in an increase in the strength properties of 15 per cent to even 30 per cent.

The rate of change in strength with changes of specific gravity is usually greater in individual specimens of a single species than in the averages for a number of species. This is illustrated by a comparison of figures 1 and 2. Figure 1 indicates that the modulus of rupture varies as the 5/4 power of the specific gravity when various species are considered, while figure 2 indicates that the relation of the crushing strength of individual specimens of white ash varies as the 3/2 power of the specific gravity. The modulus of rupture of spruce and of numerous other species has been found to vary as the 3/2 power of the specific gravity. Shock-resisting ability and other important properties vary as even higher powers of specific gravity. If an important airplane part is from wood 10 per cent below the specific gravity given in the speci-

fications, it will not be just 10 per cent but at least 14.5 per cent inferior and perhaps more, depending on which particular property is of greatest importance in the part in question. If the specific gravity is 20 per cent low, the inferiority will not be less than 28.4 per cent. The

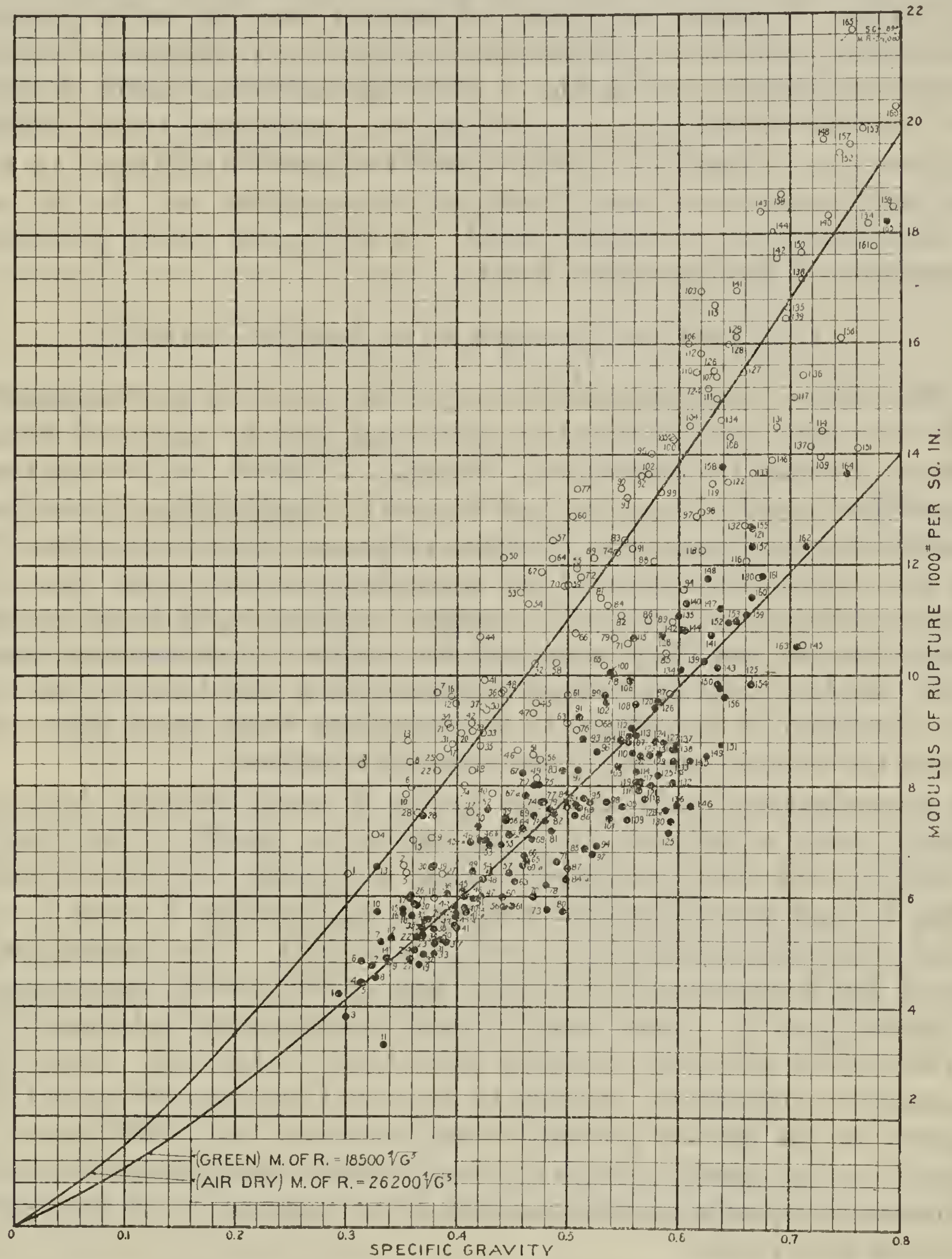

Fig. 1.—Relation between the modulus of rupture and specific gravity of various American woods.

lighter pieces of wood are usually exceedingly brash, especially when dry. The importance of admitting no material for airplane construction of lower specific gravity than given in the specifications is evident.

List of species and reference numbers for figure 1.

HARDWOODS.

Species.	Locality.	Reference No.
Alder, red	Washington	30
Ash:		
Biltmore	Tennessee	91
Black	Michigan	60
Do	Wisconsin	70
Blue	Kentucky	99
Green	Louisiana	93
Do	Missouri	100
Pumpkin	do	79
White	Arkansas	106
Do	New York	128
Do	West Virginia	83
Aspen	Wisconsin	23
Largetooth	do	20
Basswood	Pennsylvania	12
Do	Wisconsin	5
Beech	Indiana	110
Do	Pennsylvania	98
Birch:		
Paper	Wisconsin	73
Sweet	Pennsylvania	129
Yellow	do	107
Do	Wisconsin	103
Buckeye, yellow	Tennessee	9
Buckthorn, cascara	Oregon	84a
Butternut	Tennessee	27
Do	Wisconsin	21
Chinquapin, western	Oregon	48b
Cherry:		
Black	Pennsylvania	72
Wild red	Tennessee	24
Chestnut	Maryland	46
Do	Tennessee	40
Cottonwood, black	Washington	6
Cucumber tree	Tennessee	59
Dogwood:		
Flowering	do	151
Western	Oregon	125a
Elder, pale	do	69a
Elm:		
Cork	Wisconsin, Marathon County.	126
Do	Wisconsin, Rusk County.	
Slippery	Indiana	102
Do	Wisconsin	74
White	Pennsylvania	55
Do	Wisconsin	53
Greenheart		165
Gum:		
Black	Tennessee	68
Blue (Eucalyptus)	California	147
Cotton	Louisiana	76
Red	Missouri	54
Hackberry	Indiana	90
Do	Wisconsin	78
Haw, pear	do	146
Hickory:		
Big shellbark	Mississippi	135
Do	Ohio	154
Butternut	do	139
Mockernut	Mississippi	144
Do	Pennsylvania	159
Do	West Virginia	155
Nutmeg	Mississippi	112
Pignut	do	148
Do	Ohio	157

Species.	Locality.	Reference No.
Hickory—Continued.		
Pignut	Pennsylvania	160
Do	West Virginia	161
Shagbark	Mississippi	140
Do	Ohio	152
Do	Pennsylvania	143
Do	West Virginia	153
Water	Mississippi	141
Holly, American	Tennessee	87
Hornbeam	do	149
Laurel, mountain	do	145
Locust:		
Black	do	158
Honey	Indiana	162
Madrona	California	101
Do	Oregon	128a
Magnolia	Louisiana	66
Maple:		
Oregon	Washington	58
Red	Pennsylvania	69
Do	Wisconsin	92
Silver	do	56
Sugar	Indiana	104
Do	Pennsylvania	108
Do	Wisconsin	124
Oak:		
Bur	do	125
California black	California	80
Canyon live	do	163
Chestnut	Tennessee	121
Cow	Louisiana	133
Laurel	do	116
Post	Arkansas	130
Do	Louisiana	137
Red	Arkansas	119
Do	Indiana	118
Do	Louisiana	117
Do	Tennessee	97
Highland Spanish	Louisiana	94
Lowland Spanish	do	142
Swamp white	Indiana	150
Tanbark	California	115
Water	Louisiana	111
White	Arkansas	132
Do	Indiana	138
Do	Louisiana, Richland Parish.	136
Do	Louisiana, Winn Parish.	131
Willow	Louisiana	109
Yellow	Arkansas	122
Do	Wisconsin	105
Osage orange	Indiana	164
Poplar, yellow (tulip tree).	Tennessee	35
Rhododendron, great	do	85
Sassafras	do	51
Serviceberry	do	156
Silverbell tree	do	49
Sourwood	do	89
Sumac, staghorn	Wisconsin	61
Sycamore	Indiana	63
Do	Tennessee	65
Umbrella, Fraser	do	45
Willow:		
Black	Wisconsin	11
Western black	Oregon	43a
Witch hazel	Tennessee	114

List of species and reference numbers for figure 1—Continued.

CONIFERS.

Species.	Locality.	Reference No.
Cedar:		
Incense	California	26
Western red	Montana	2
Do	Washington	10
White	Wisconsin	1
Cypress, bald	Louisiana	62
Douglas fir	California	45a
Do	Oregon	67a
Do	Washington, Chehalis County.	46a
Do	Washington, Lewis County.	75
Do	Washington and Oregon.	67
Do	Wyoming	84
Fir:		
Alpine	Colorado	4
Amabilis	Oregon	39
Do	Washington	18
Balsam	Wisconsin	14
Grand	Montana	36
Noble	Oregon	16
White	California	17
Hemlock:		
Black	Montana	47
Eastern	Tennessee	52
Do	Wisconsin	15
Western	Washington	50
Larch, western	Montana	84
Do	Washington	64
Pine:		
Cuban	Florida	127
Jack	Wisconsin	43
Jeffrey	California	33
Loblolly	Florida	88
Lodgepole	Colorado	31
Do	Montana, Gallatin County.	35a
Pine—Continued.		
Lodgepole	Montana, Granite County.	41a
Do	Montana, Jefferson County.	40a
Do	Wyoming	34
Longleaf	Florida	123
Do	Louisiana, Lake Charles.	113
Do	Louisiana, Tangipahoa Parish.	96
Do	Mississippi	95
Norway	Wisconsin	57
Pitch	Tennessee	71
Pond	Florida	86
Shortleaf	Arkansas	77
Sugar	California	22
Table Mountain	Tennessee	82
Western white	Montana	42
Western yellow	Arizona	19
Do	California	37
Do	Colorado	41
Do	Montana	32
White	Wisconsin	25
Redwood	California, Albion	28
Do	California, Korbel	13
Spruce:		
Engelmann	Colorado, Grand County.	8
Do	Colorado, San Miguel County.	3
Red	New Hampshire	44
Do	Tennessee	29
White	New Hampshire	7
Do	Wisconsin	38
Tamarack	do	81
Yew, western	Washington	134

The minimum strength values which may be expected of a particular lot of lumber can be raised a good deal by eliminating a relatively small portion of the lighter material. This lightweight material can, as a rule, be detected by visual inspection. In order to train the visual inspection and to pass judgment on questionable individual pieces, frequent specific gravity determinations are necessary.

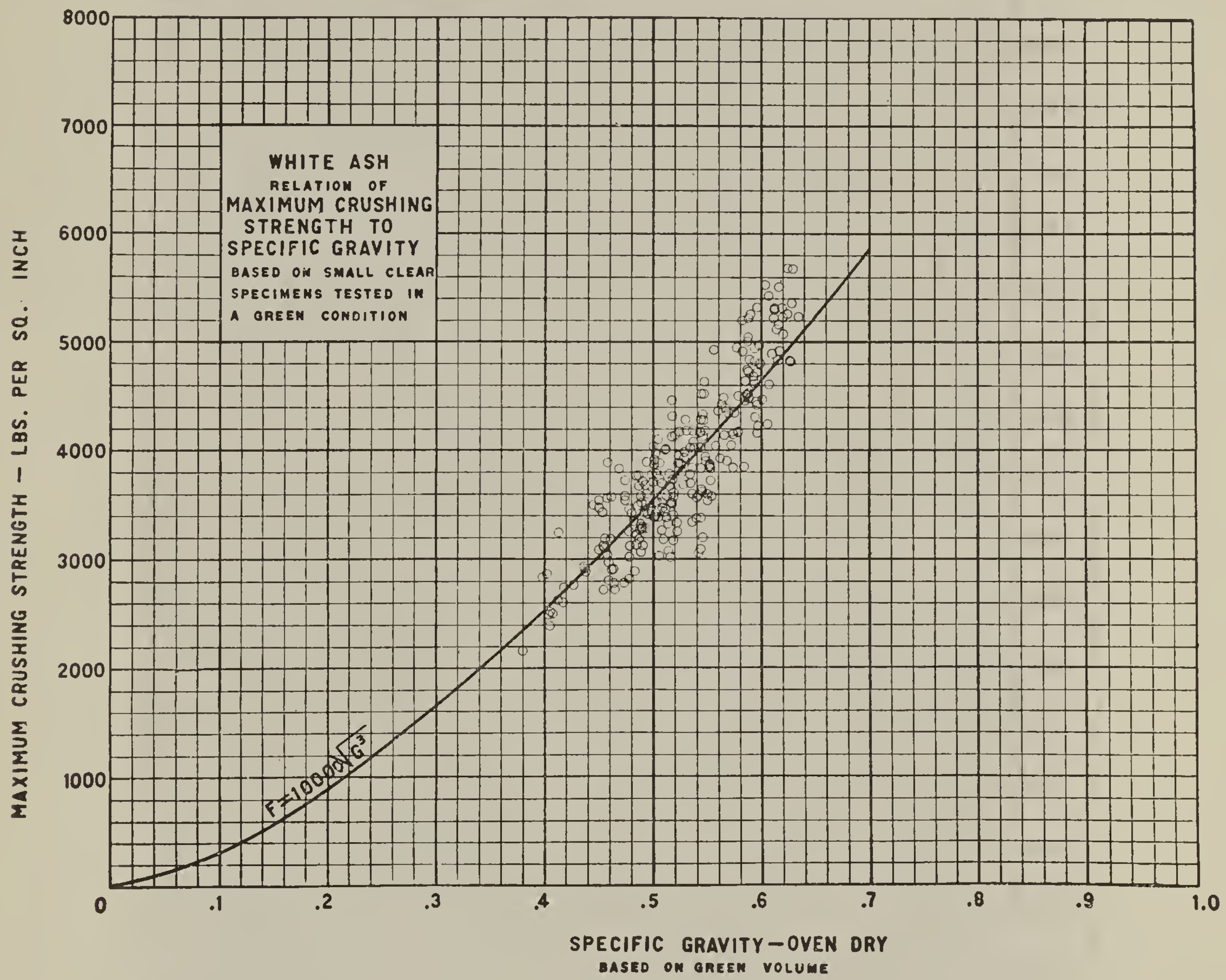

Fig. 2.

A specific gravity determination is relatively simple to make, and it is probably a better criterion of all the qualities of the piece than any single mechanical test which is likely to be applied; also the specific gravity determinations need no adjustment such as would be necessary on account of the varied conditions of a mechanical test.

VARIATION OF STRENGTH WITH MOISTURE CONTENT.

When a piece of green or wet wood is dried, no change in mechanical properties takes place until the fiber-saturation point is reached.* The changes beyond this point for small test specimens free from defects and very carefully dried are illustrated in figures 3 and 4. These

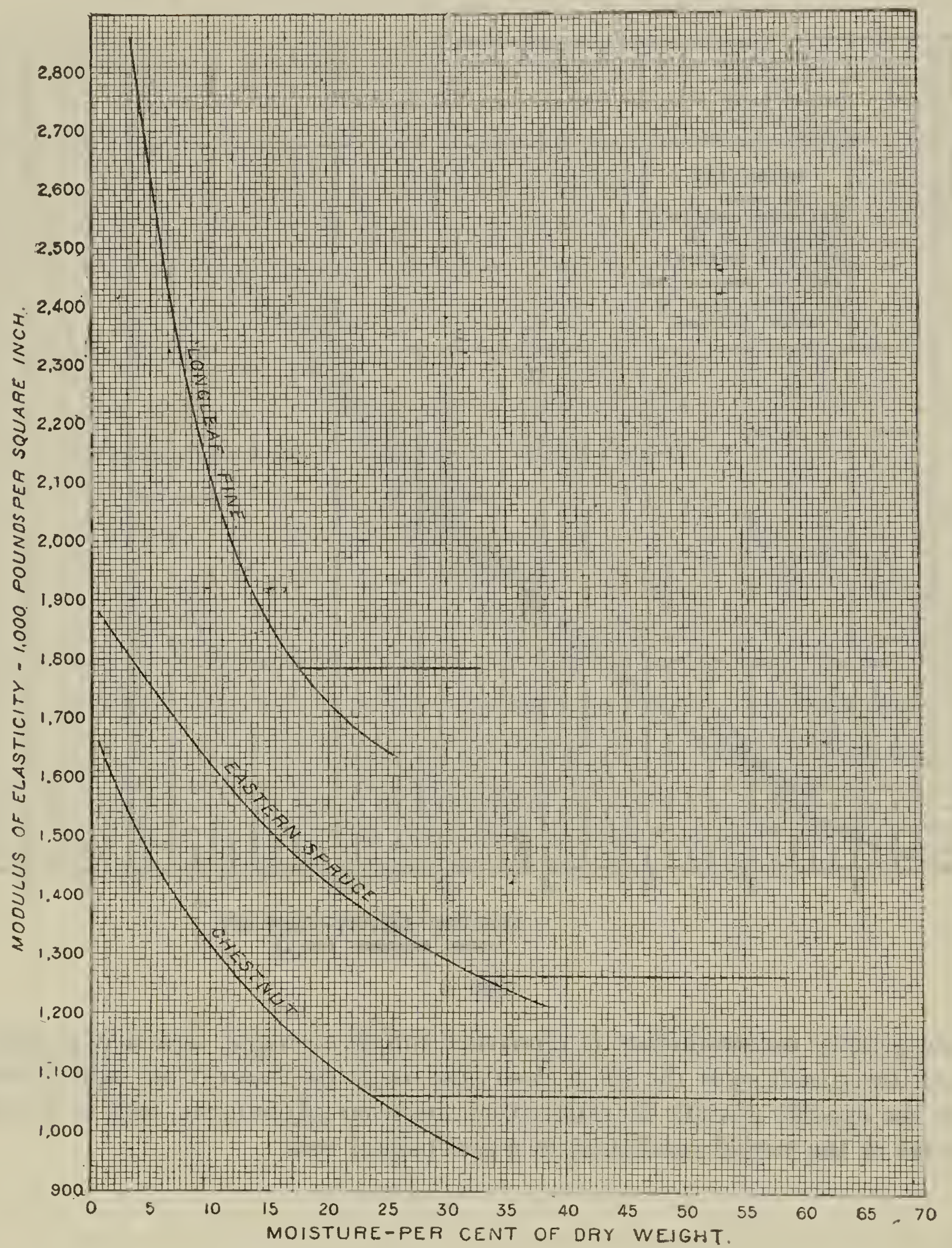

Fig. 3.—Relation between the stiffness (modulus of elasticity) in binding and moisture content, for three species.

figures show that the moisture content at the fiber-saturation point differs for different species. It will be noted that the influence of moisture is smaller in tests of shearing strength and compression perpendicular to the grain than in bending and compression parallel to the grain.

* The eucalypts and some of the oaks are exceptions to this rule.

Furthermore, there is no definite break at or near the fiber-saturation point in the moisture-strength curves for shear and compression perpendicular to the grain. In the case of shear this failure to show large increases in strength is probably due to checks which form as the material dries.

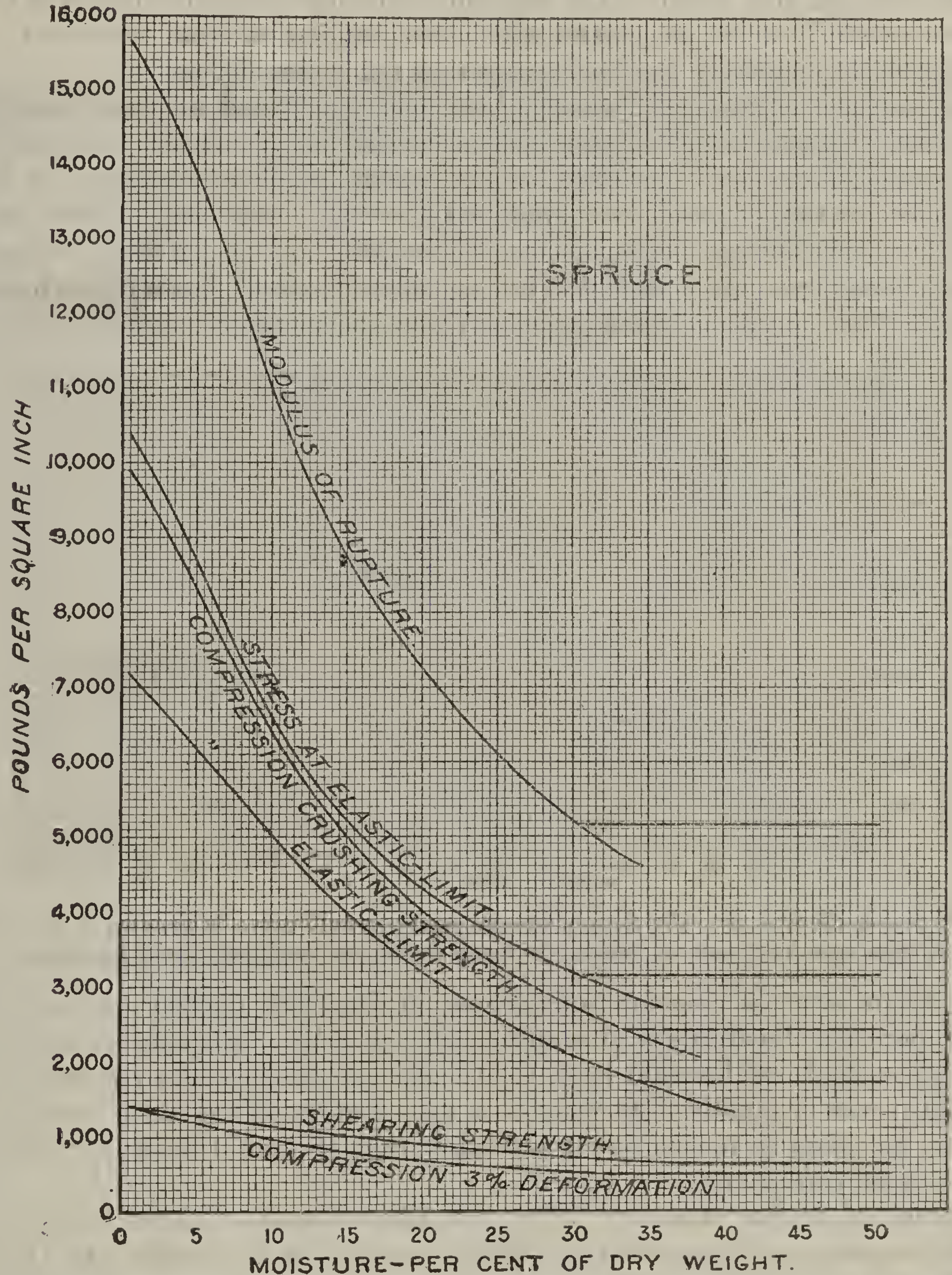

Fig. 4.—Comparison of the relation between strength and moisture content for red spruce in various kinds of tests. (The lowest curve is for compression at right angles to grain.)

The moisture content at the fiber-saturation point varies not only with the species but with different specimens of the same species. The percentage change of strength which results from a given change of moisture also varies with the species and with individual specimens of the species.

The form of the curves shown in figures 3 and 4 applies only to small clear pieces very carefully dried and having a practically uniform moisture content throughout. If the moisture be unequally distributed in the specimen, as is the case of large timbers rapidly dried or of "case-hardened" pieces, the outer shell may be drier than the fiber-saturation point while the inside still contains free water. The resulting moisture-strength curve will be higher than the curve from carefully dried pieces and will be so rounded off from the driest to the wettest condition as to obscure entirely the fiber-saturation point (see fig. 5).

The increase in strength which takes place in drying wood depends upon the specimen and upon the care with which the drying process is carried out. Furthermore, while the strength of the fibers is no doubt greatly increased by any reasonable drying process, the increase of the strength of a piece of timber taken as a whole may be very much less. Knots are more or less loosened, checking takes place, and shakes are further developed. In large bridge and building timbers these effects are so great that it is not considered safe to figure on such timbers having greater strength when dry than when green. When the pieces are small and practically free

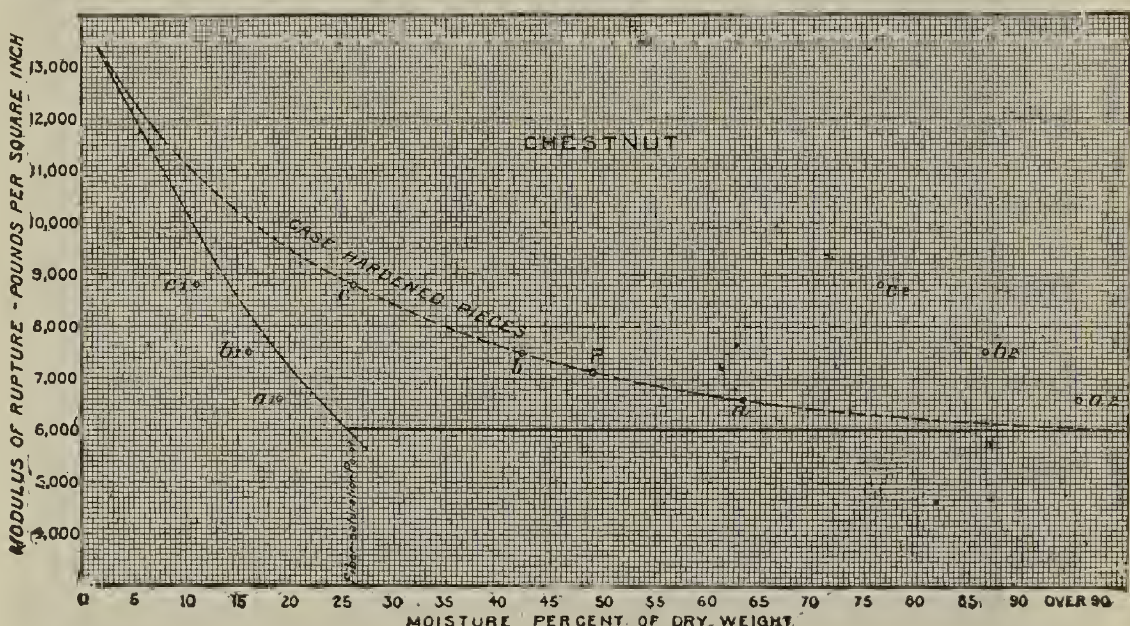

Fig. 5.—Effect of case-hardening upon the form of the moisture-strength curve in bending tests. The upper curve is from case-hardened specimens, the lower curve from uniformly dired specimens.

from defects, as in airplane construction, proper drying with careful control of temperature and humidity increases the strength of material very greatly. In whatever way wood is dried, upon its being resoaked and brought back to the original green or wet condition it is found to be weaker than it was originally. So when it is said that wood has been injured in the drying process it must be taken to mean that it is weaker than it should have been after drying and while still in a dried condition.

When a stick of timber dries out below the fiber-saturation point (that is, when it has lost all its free moisture and the moisture begins to leave the cell walls), the timber begins to shrink and change in its mechanical properties. Also numerous stresses are set up within the timber. Under severe or improper drying conditions the stresses may be great enough to practically ruin the material for purposes where strength is important. Improper drying conditions, however, do not of necessity mean fast drying conditions. When properly dried, the timber gains in its fiber stress at elastic limit, its modulus of rupture, maximum crushing strength, etc. It bends farther at the elastic limit when dry than when green, but does not bend so far at the maximum load. After having been bent to the maximum load dry timber breaks more suddenly than green timber of the same species—that is, dry timber is more brash than green, although it withstands greater stresses and is stiffer.

DEFECTS AFFECTING STRENGTH.

DIAGONAL AND SPIRAL GRAIN.

Diagonal grain is produced when the saw cut is not made parallel to the direction of the fibers. It can usually be avoided by careful sawing unless it is caused by crooks in the log. Spiral grain, on the other hand, results from a spiral arrangement of the wood fibers in the tree.

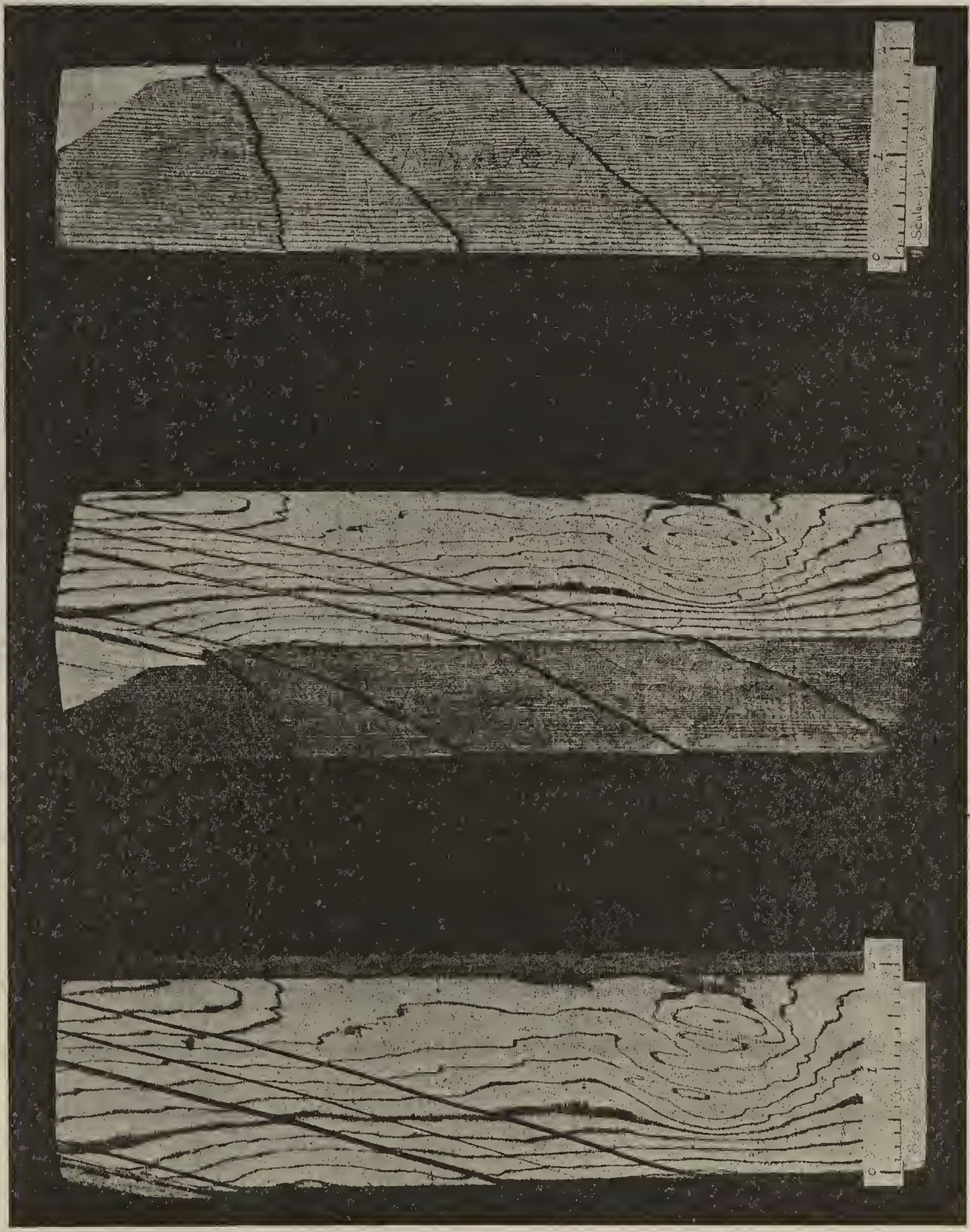

Fig. 6.—Spiral grain in Sitka spruce.

If a log is spiral grained, it is impossible to secure straight-grained material, except in small pieces, from the spiral-grained part. The effect of spiral grain is illustrated in figure 6, which shows three views of a piece of Sitka spruce. The center part of a log may be straight grained and the outer part spiral grained or vice versa.

Figures 7 to 14, inclusive, show the weakening effect of spiral or diagonal grain upon various strength properties of Sitka spruce and Douglas fir. The data are based upon about 1,400 static bending tests, made upon clear specimens, third point loading, 45-inch span. Similar impact bending tests have shown similar weakening with increasing slope of grain.

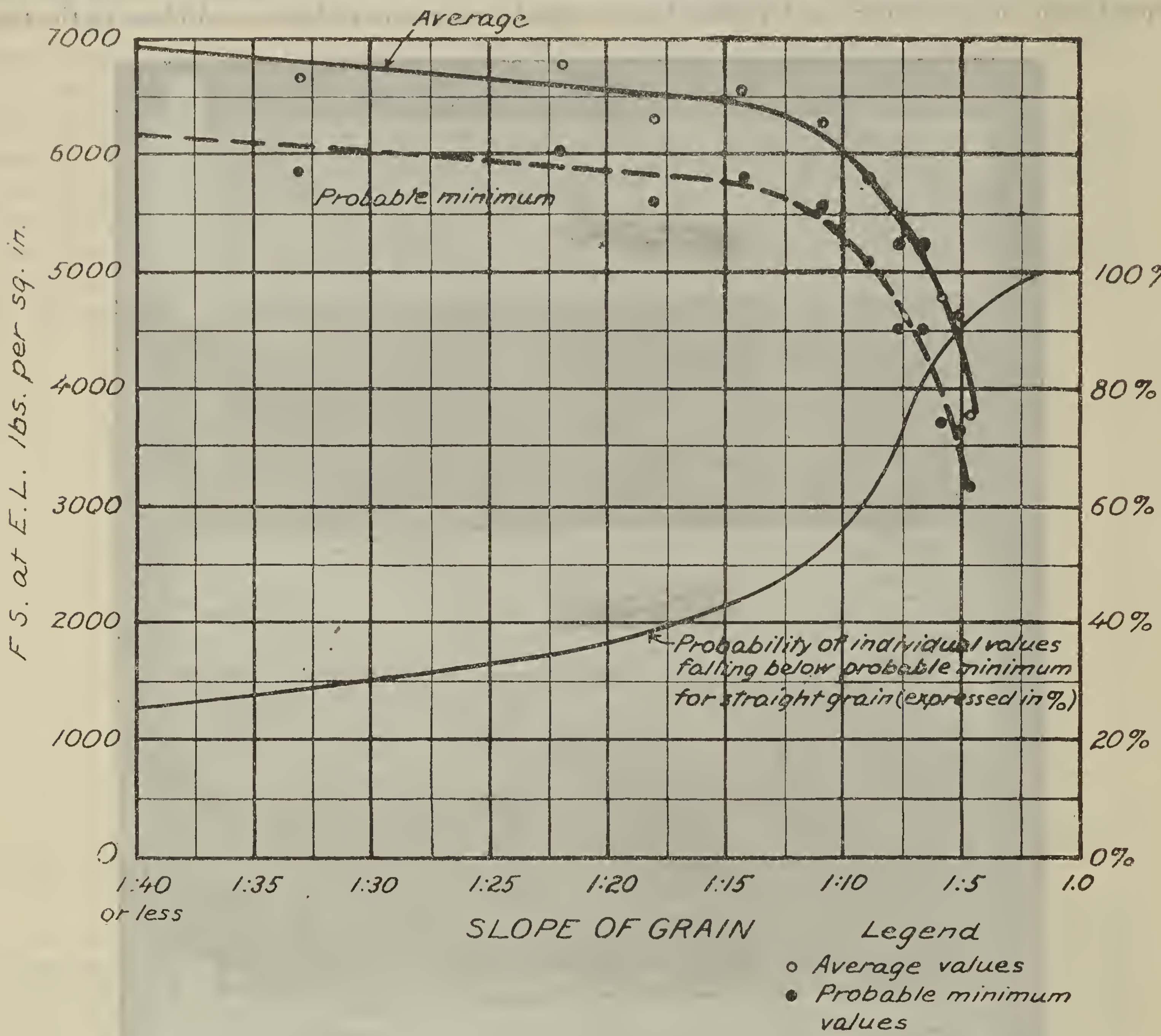

Fig. 7.—The effect of spiral and diagonal grain on the fiber stress at the elastic limit; Sitka spruce.

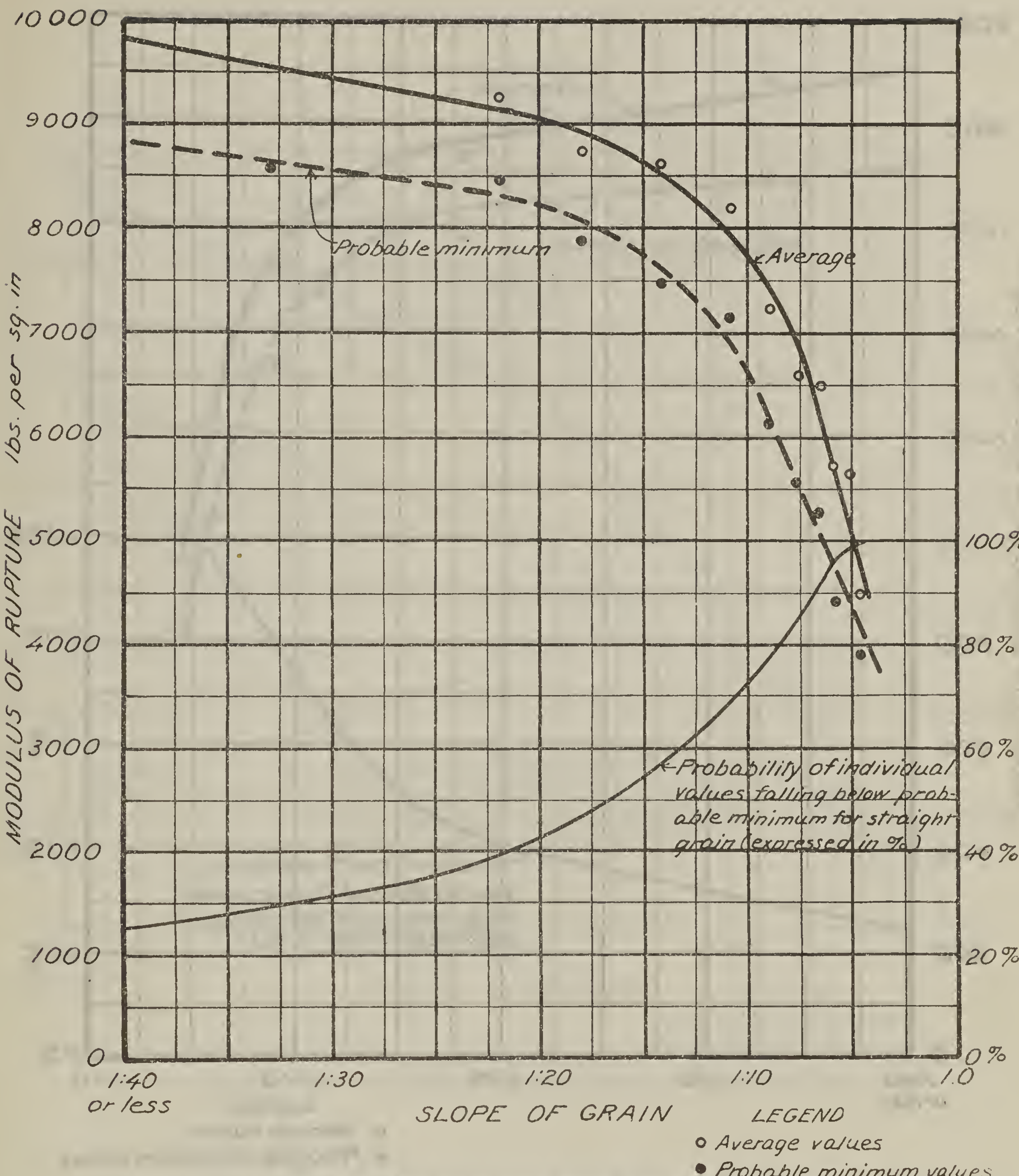

Fig. 8.—The effect of spiral and diagonal grain on the modulus of rupture; Sitka spruce.

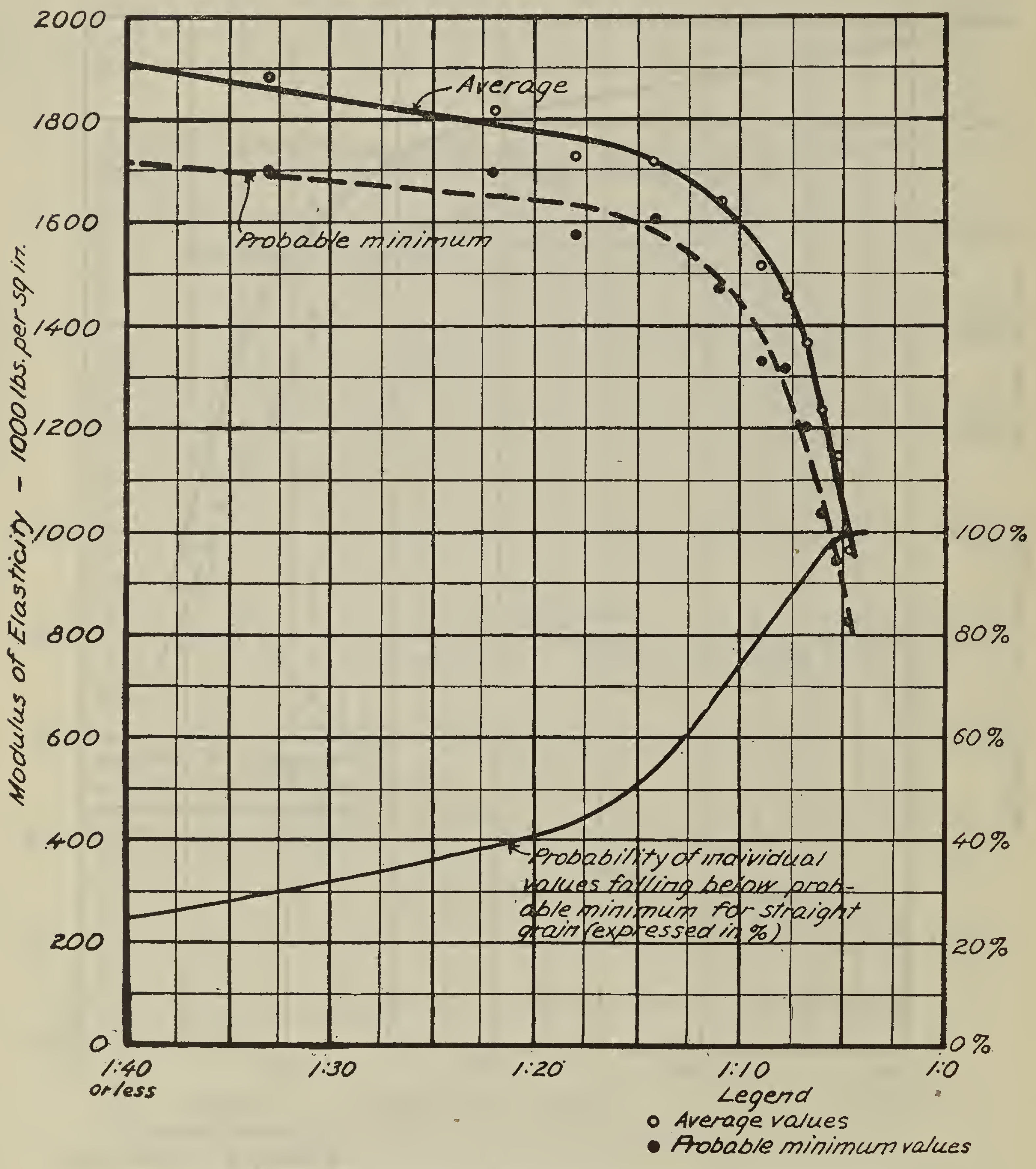

Fig. 9.—The effect of spiral and diagonal grain on the modulus of elasticity; Sitka spruce.

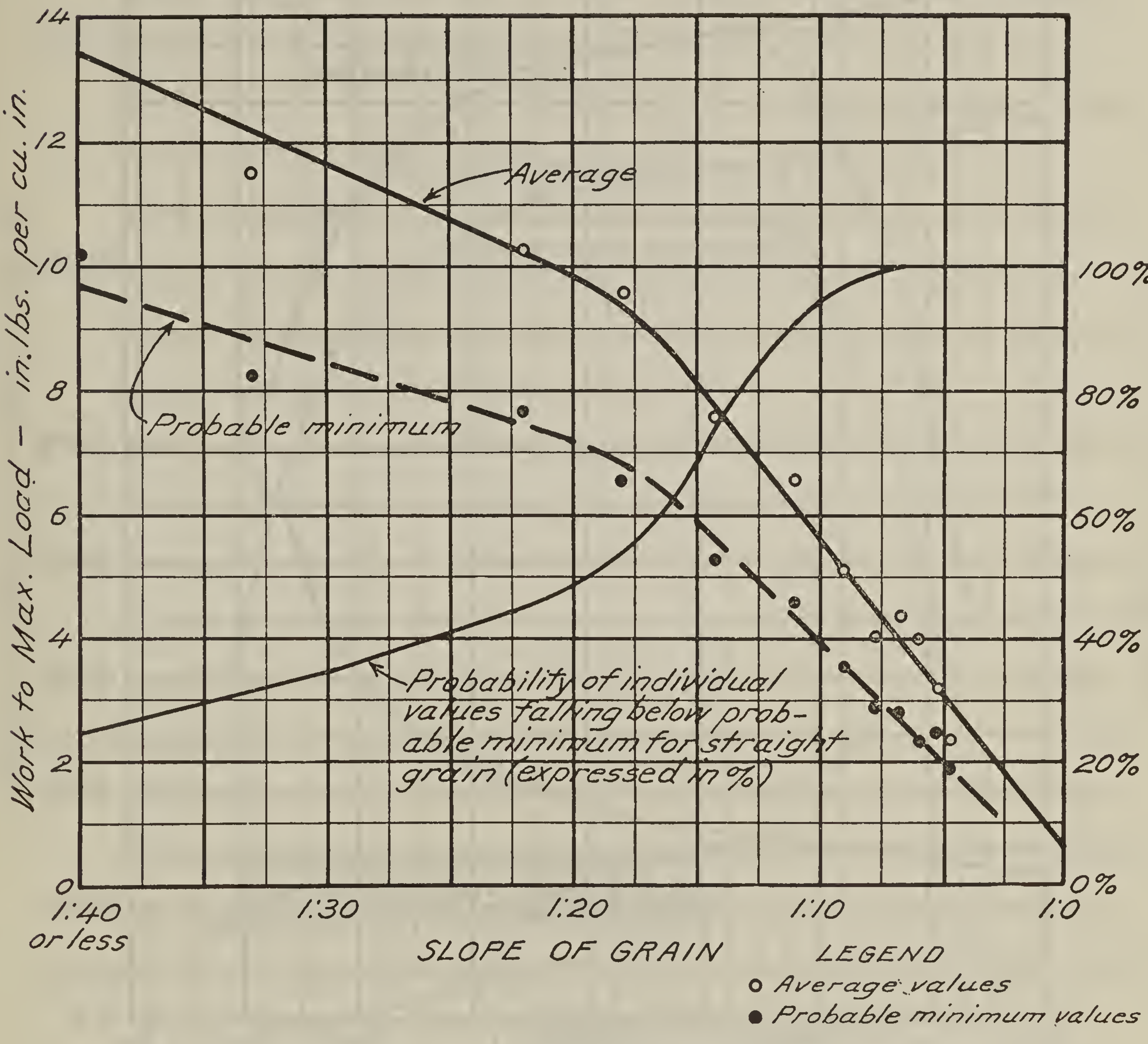

Fig. 10.—The effect of spiral and diagonal grain on the work to maximum load; Sitka spruce.

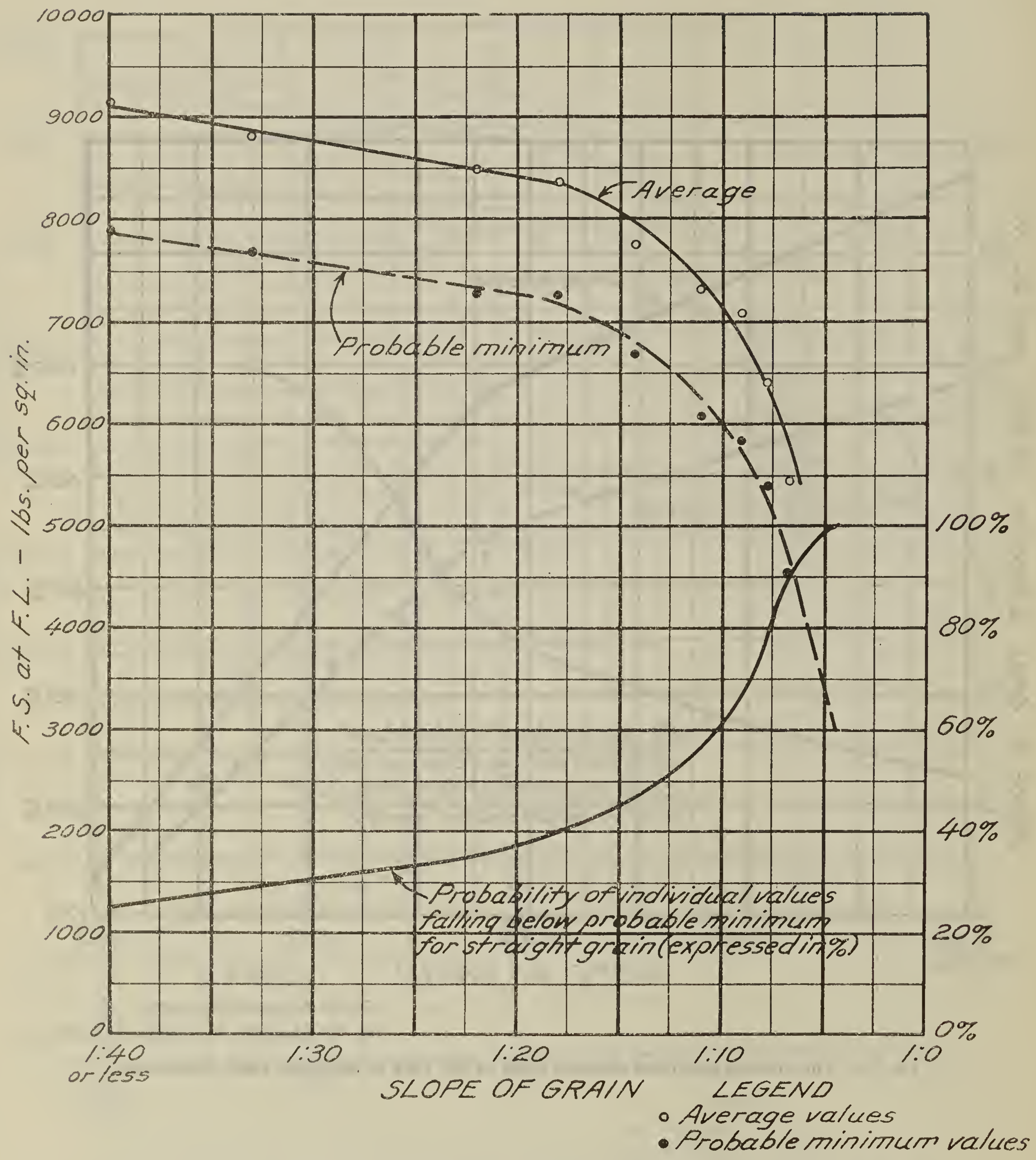

Fig. 11.—The effect of spiral and diagonal grain on the fiber stress at the elastic limit; Douglas fir.

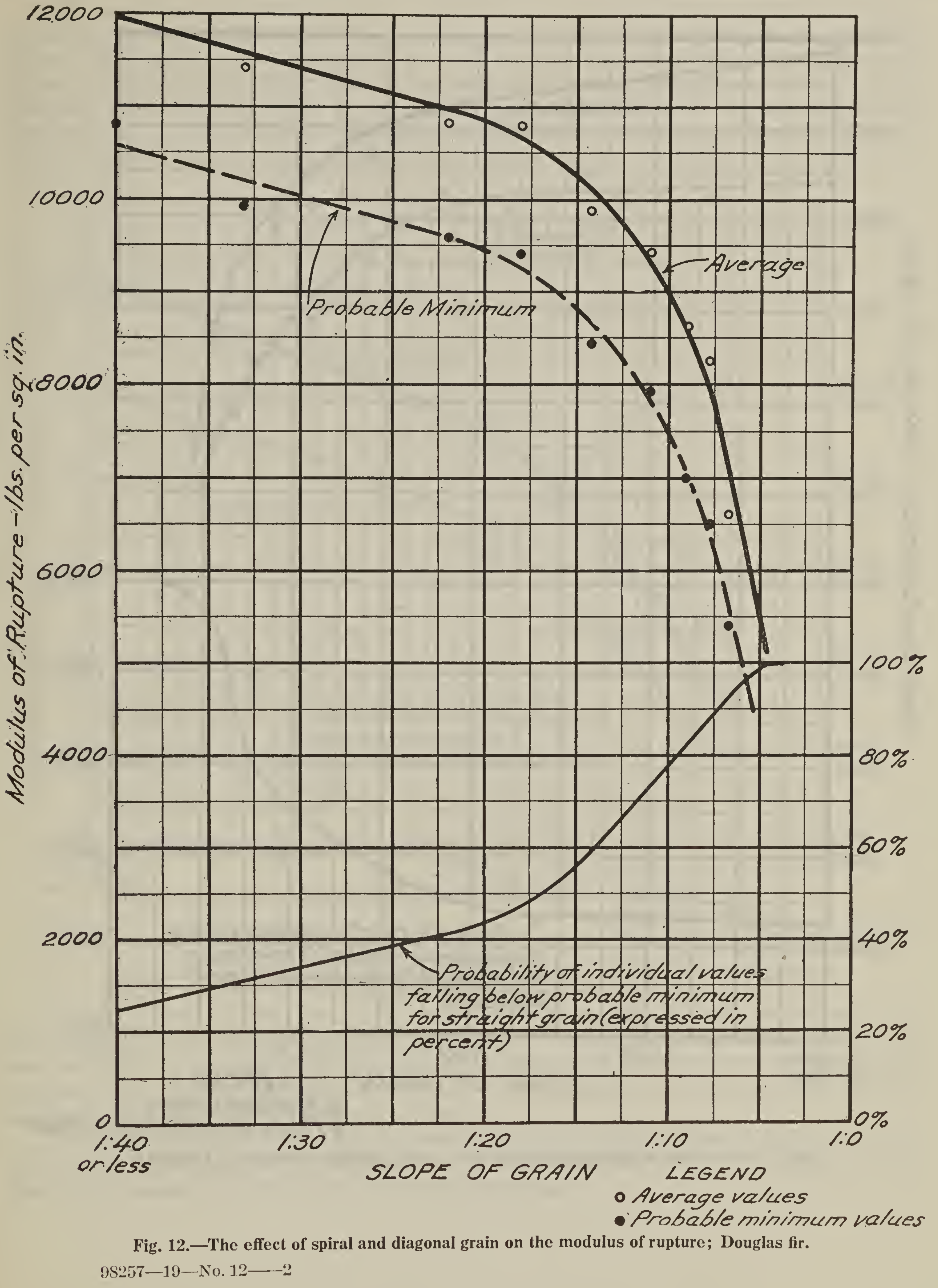

Fig. 12.—The effect of spiral and diagonal grain on the modulus of rupture; Douglas fir.

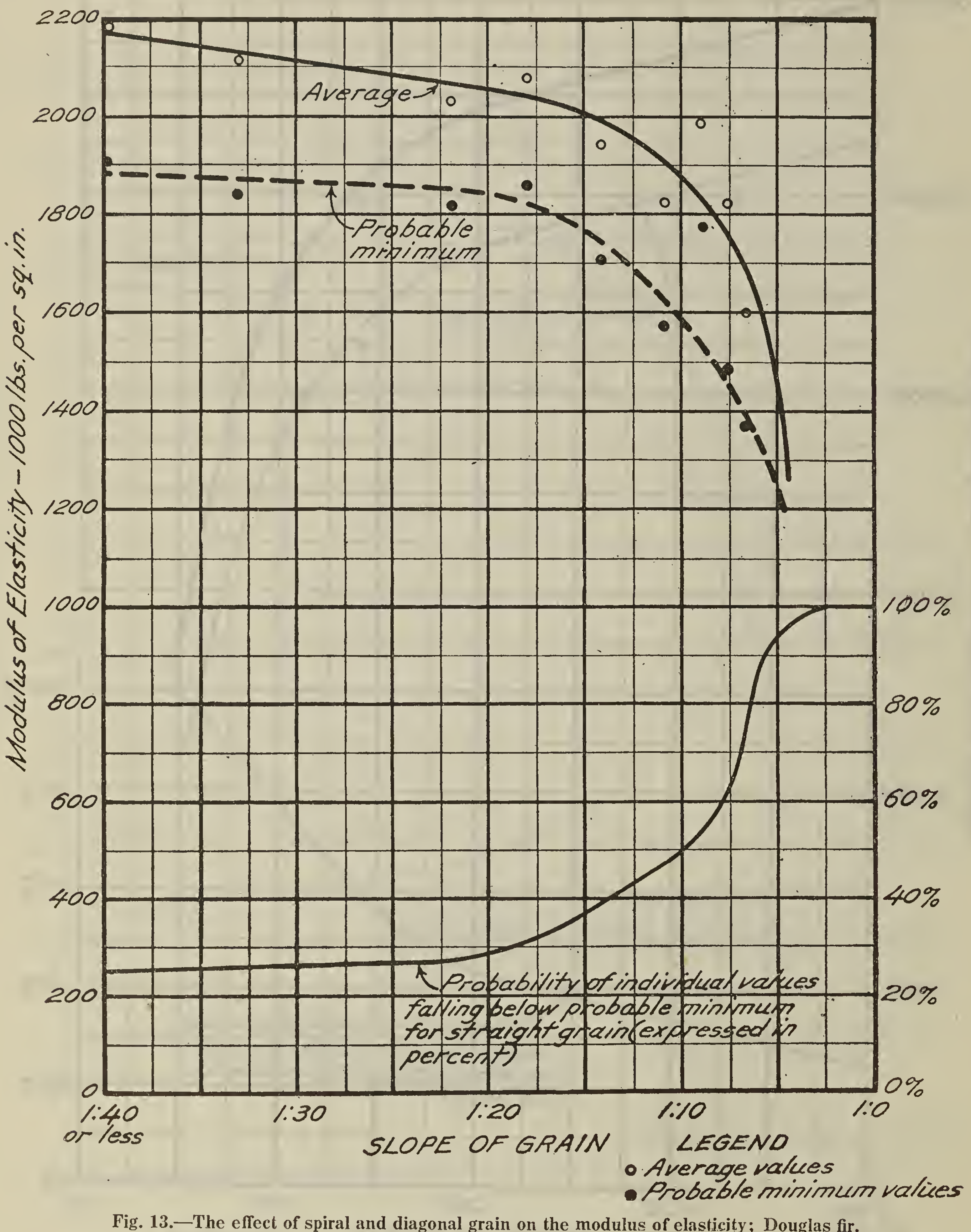

Fig. 13.—The effect of spiral and diagonal grain on the modulus of elasticity; Douglas fir.

The tests were made upon seasoned material, but since the moisture content of the individual specimens varied somewhat, it was necessary to reduce such properties as are materially affected by changes in moisture content to a uniform basis before comparisons could be made. Therefore, the values for fiber stress at the elastic limit, modulus of rupture, and modulus of elasticity have been reduced to 11 per cent by means of an empirical exponential formula. The work to the maximum load values were not reduced to a uniform moisture basis, since the correction would have been very small, and no greater accuracy would have been insured.

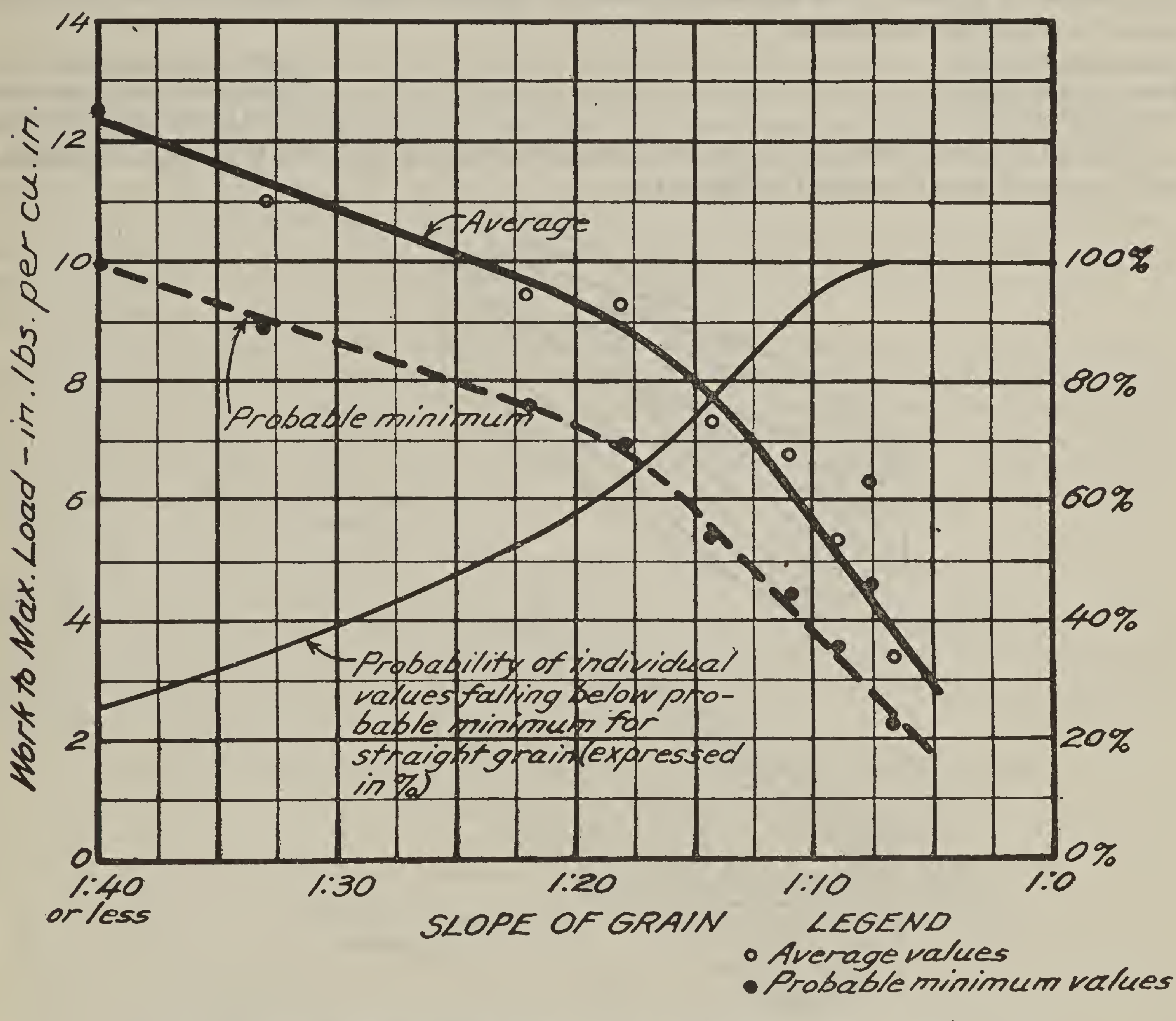

Fig. 14.—The effect of spiral and diagonal grain on the work to maximum load; Douglas fir.

In addition to the curve for average values based on test data, a curve for probable minimum values (broken line) was calculated and plotted. A third curve was also drawn showing the probability of individual values falling below the probable minimum value for straight-grained material. This probability is expressed in per cent and, as is to be expected, increases greatly as the slope of the grain becomes steeper.

The rate of falling off in strength increases abruptly at a slope between 1 in 20 and 1 in 15, and therefore this slope may be considered to be the critical one. It is to be noted, however, that even at slopes at 1 in 20 there is a decided weakening.

As a result of these tests it is recommended that for purposes of design the following values for moduli of rupture for spruce at 15 per cent moisture and different slopes of spiral or diagonal grain be strictly adhered to:

From straight to 1 in 25	7,900 pounds per square inch.
From 1 in 25 to 1 in 20	7,000 pounds per square inch.
From 1 in 20 to 1 in 15	5,500 pounds per square inch.

The effect of spiral grain upon the maximum crushing strength is much smaller than upon the modulus of rupture. The following stresses for different slopes of grain may be used with safety for compression members:

From straight to 1 in 25	4,300 pounds per square inch.
From 1 in 25 to 1 in 20	4,200 pounds per square inch.
From 1 in 20 to 1 in 15	3,800 pounds per square inch.

When the annual rings run diagonally across the end of a piece the true slope of diagonal grain can be obtained as shown by figure 15*a*.

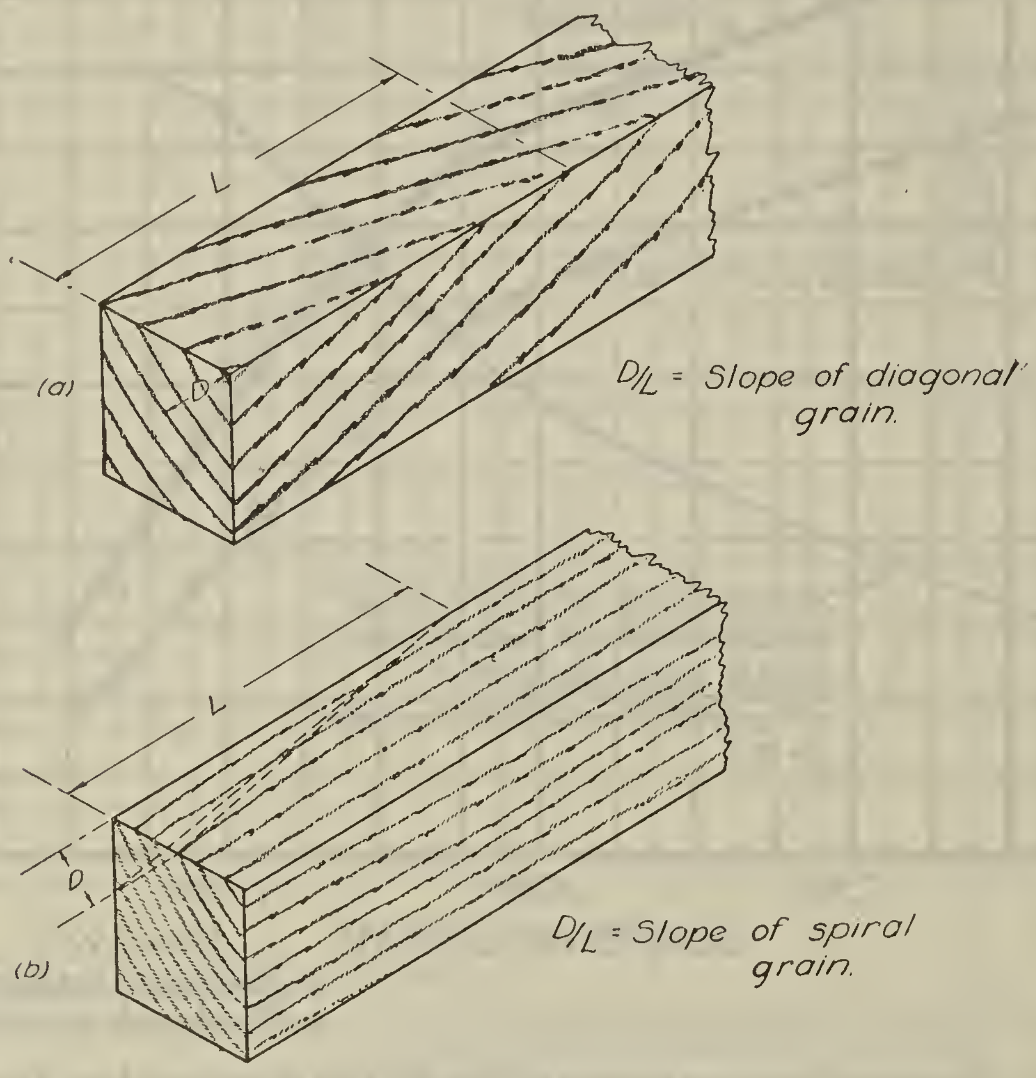

Fig. 15.—The measurement of the slope of diagonal and spiral grain.

The direction of spiral grain is indicated on a tangential (flat sawn) face by the direction of the resin ducts. These ducts, however, are often difficult to see. Drops of ink placed on tangential faces and allowed to spread are sometimes used to test for spiral grain. The ink will tend to follow the angle of the grain. The direction of spiral grain is, however, not given correctly by resin ducts or by spreading of ink unless these tests be applied to a truly tangential face. In figure 15, for instance, resin ducts or spreading of ink would be practically parallel to the edges whether the material was spiral grained or not. In such cases spiral grain can be detected only by splitting on a radial line (Fig. 15*b*) or by raising small splinters and observing if they have a tendency to tear deeper and deeper.

KNOTS.

The effect of knots depends upon their location with respect to the stresses to which the piece will be subjected, as well as upon their size and character. None but sound knots, firmly attached, should be permitted. Obviously, knots of any considerable size can not be allowed in any airplane parts because the parts themselves are comparatively small in cross section. Since the weakening effect of knots results from their disturbance of normal arrangement of fibers, their seriousness can best be decided from a consideration of the grain.

PITCH POCKETS.

Tests recently completed on 112 solid Douglas fir wing beams, made especially to study the effect of pitch pockets upon the strength of beams indicate that this effect may have been overrated in previous specifications. The tests were made over a 72-inch span under third-point loading. The following conclusions from these tests are presented in the form of specifications, and are intended to be applied to spruce and fir wing beams:

(*a*) In portions of the length where a slope of grain of 1 in 25 is the maximum allowed, pitch pockets 1½ inches in length and not to exceed one-eighth of an inch in width or depth may be allowed in any portion of the section except the outer quarters of the flange. No pitch pockets to be allowed in outer quarters of flange.

(*b*) Where a slope of spiral grain of 1 in 20 is allowed pitch pockets 2 inches in length and not to exceed one-fourth inch in width or depth may occur any place in the section except in the outer quarters of the flange. No pitch pockets to be allowed in outer quarters of flange.

(*c*) Where a slope of grain of 1 to 15 is allowed pitch pockets 1½ inches in length and one-fourth inch in width or depth may occur in the outer quarters of the flange, and pitch pockets 3 inches in length and one-fourth inch in width or depth may occur in any other portion of the section.

(*d*) Pitch pockets occurring in the web may not be closer together than 20 inches. If they are in the same annual ring, they may not be closer together than 40 inches. In other portions of the section these distances may be 10 inches and 20 inches, respectively.

Combining this specification with a knot and spiral-grain specification, the following table has been prepared; it is the intention that this table be used in drafting parts specifications for spruce and fir wing beams:

TABLE 1.—*Size and quantity of defects allowable with different slopes of grain.*

Allowable slope in grain not exceeding—	Knots.		Pitch pockets.	
	Maximum diameter permitted.	Minimum distance between any two.	Maximum length permitted.	Maximum width or depth permitted.
	Inches.	*Inches.*	*Inches.*	*Inches.*
1 inch in 25	$\frac{1}{8}$	10	1½	$\frac{1}{8}$
1 inch in 20	$\frac{3}{16}$	12	2	$\frac{1}{4}$
1 inch in 15	$\frac{1}{2}$	20	3	$\frac{1}{4}$

Supplementing the table are the following clauses:

1. All knots must be sound.
2. No defects must fall or cause irregular grain greater in slope than that allowable for cross grain in the outer quarter of the upper or lower flange; except that where a slope of 1 in 15 is allowed, pitch pockets 1½ inches long and one-fourth inch wide or deep may be permitted.
3. Pitch pockets occurring in the web may not be closer together than 20 inches. If they are in the same annual ring, they may not be closer together than 40 inches. In other portions of the section these distances may be 10 inches and 20 inches, respectively.
4. The equivalent of the diameters specified may be allowed in a number of smaller knots, provided that they are not close together.

COMPRESSION FAILURES AND "CROSS BREAKS."

All material containing compression failures and "cross breaks" should be eliminated from airplane parts where strength is of importance. The cause of certain "cross breaks" near the center of large logs such as are quite frequently found in mahogany is not known. Compression failures, which are, in fact, of the same nature as "cross breaks," are known frequently to be due to injury by storm in the standing trees, to carelessness in felling trees across logs, to unloading from a car across a single skid, or to injury during manufacture.

While some compression failures are so pronounced as to be unmistakable, others are difficult to detect. They appear as wrinkles across the face of the piece. Compression failures not readily apparent to the eye may seriously reduce the bending strength of wood and its shock-resisting ability, complete failure occurring suddenly along the plane of injury.

Figure 16 shows four samples of African mahogany containing compression failures which occurred during growth. These samples were later tested in static bending, and in all cases the compression failures developed during test followed those originally occurring in the samples. This is illustrated in figure 17.

BRASHNESS.

The term "brash," frequently used interchangeably with the term "brittle," when used to describe wood or failures in wood, indicates a lack of toughness. Brash wood, when tested in bending, breaks with a short, sharp fracture instead of developing a splintering failure and absorbs a comparatively small amount of work between the elastic limit and final failure. In impact tests brash wood fails completely under a comparatively small hammer drop.

DECAY.

The first effect of decay is to reduce the shock-resisting ability of the wood. This may take place to a serious extent before the decay has sufficiently developed to affect the strength under static load or to become evident on visual inspection. Unfortunately there is no method of detecting slight decay in wood except with a compound microscope. All stains and discolorations should be regarded with suspicion and carefully examined. It must be remembered that decay often spreads beyond the discoloration it causes and that pieces adjacent to discolored areas may already be infected. On the other hand, not all stains and discolorations are caused by decay of the wood. The blue sapstain of some hardwoods and of many coniferous woods, including spruce, and the brown stain of sugar pine are not caused by decay-producing organisms and do not weaken the wood.

INTERNAL OR INITIAL STRESSES IN WOOD.

WOOD FIBERS UNDER STRESS IN THE TREE.

Wood products are quite similar to metal castings as regards internal stresses. It is probable that wood fibers are continually under stress of some kind. The fact that freshly cut logs of some species split through the center (this frequently happens as the result of heavy shocks or jars and without the use of a wedge) is evidence of some tensile stresses in the outer portion of the tree and compression in the inner portion. These stresses are independent of the stresses due to the weight of the tree and pressure against it.

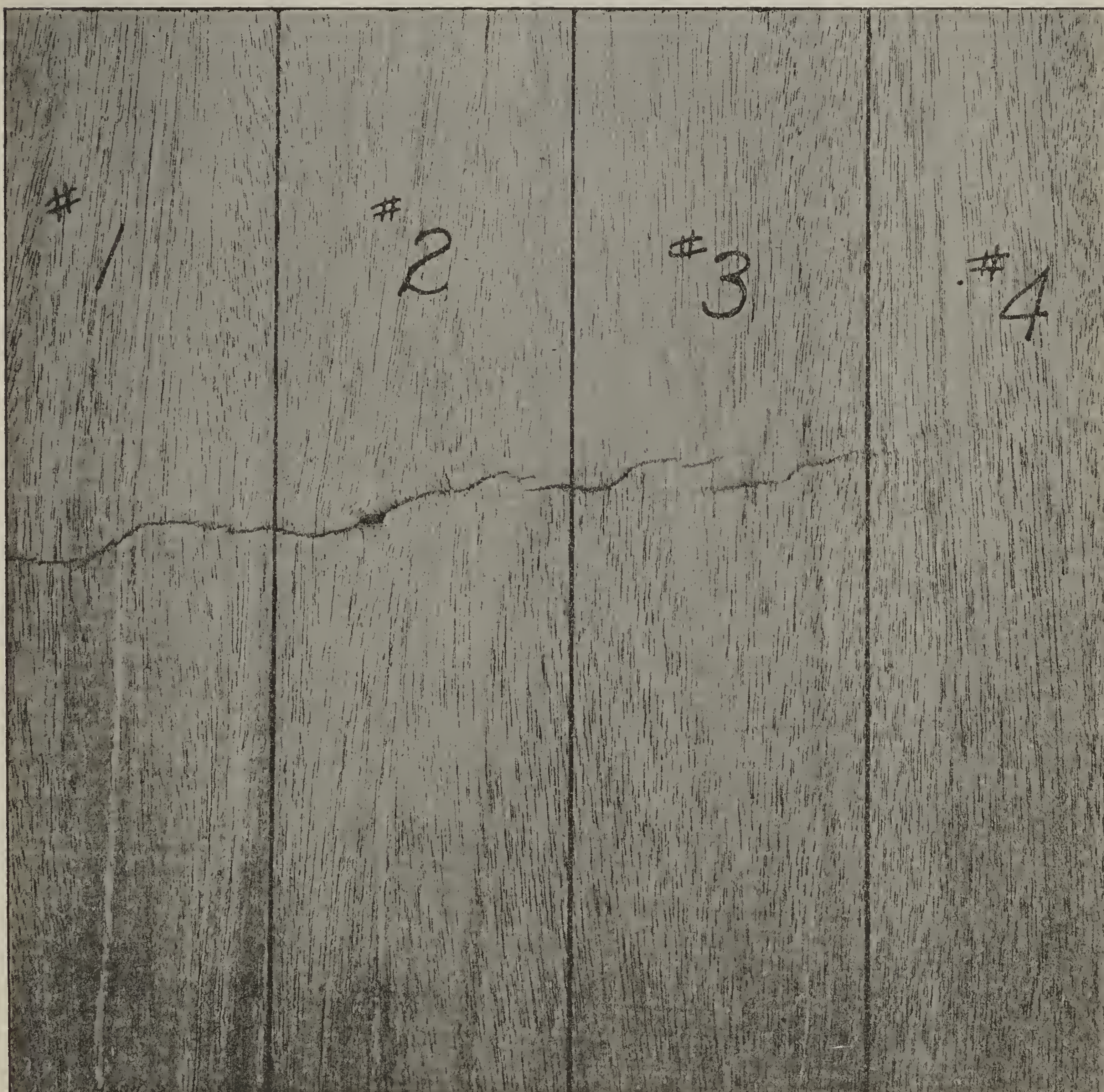

Fig. 16.—Compression failure occurring during growth. African mahogany

Fig. 17.—Influence of compression failure occurring during growth on failures in static bending. African mahogany.

INTERNAL STRESSES PRODUCED DURING DRYING.

The natural stresses may be partially or wholly relieved by sawing the tree into lumber, but other stresses are likely to be introduced by subsequent seasoning. Checking, honeycombing, warping, twisting, etc., are manifestations of the internal stresses which are produced in the drying of wood or whenever any change of moisture content takes place. Presumably such stresses are due to unequal distribution of moisture and consequent unequal shrinkage combined with more or less inherent lack of homogeneity.

Air drying for a number of years, which is practiced in some woodworking industries, has for its object the equalization of moisture and the relief of stresses induced in the early part of the drying. Careful and correct kiln drying followed by a period of seasoning under proper and controlled atmospheric conditions should produce results at least equal and probably superior to those obtained by long periods of air drying.

Relieving these internal stresses is important because they amount to an actual weakening of the material. If the fibers of a piece of wood are under stress when the piece is free, they are just that much less capable of resisting stresses of the same kind produced by exterior forces or loads applied to the piece.

INITIAL STRESSES PRODUCED IN ASSEMBLING.

When a member of any structure is stressed in assembling the structure and before any load is placed on it, it is said to be under initial stress. If the initial stress is of the same character as the stress for which the member is designed, it constitutes a weakening, for when the structure is loaded the safe working stress of the member will be reached just that much sooner. If this initial stress is opposite in character to that for which the member is designed, it amounts to a strengthening of the member, for when the structure is loaded the initial stress must be overcome before the member takes any of the stress for which it is designed.

Many of the curved parts of an airplane frame could be simply sprung to place on assembly. Were this done, they would be subjected to initial stress and usually of the same sign to which the member would later be subjected. In order to avoid initial stress, such parts are steam bent before assembly. It is desirable, of course, that this bending be so done as not to injure the material and to leave little tendency to spring back from the curves to which it is bent. In order that the material may be made sufficiently plastic to accomplish this result, it is essential that the steaming and bending be carried out while the wood is at a relatively high moisture content. If it is attempted on kiln-dry or thoroughly air-dry material, there is the tendency to spring back after the clamps are removed. Bending of such stock can not be compared to a considerable part of the bending done in other woodworking industries, where the strength of the wood is very greatly damaged by the bending process but without destroying its usefulness for the purpose for which it is intended. Some of the unexpected failures of bent parts in airplanes have doubtless been due to the initial stresses set up in the member during the bending.

WORKING STRESSES FOR WOOD IN AIRCRAFT CONSTRUCTION.

Table 2 gives strength values at 15 per cent moisture (which is probably close to the maximum moisture content of wood in a humid atmosphere) for use in airplane design, as well as the minimum specific gravity and average density which should be allowed. It is suggested that the working stresses for design be obtained by applying factors to the values for static load conditions as given in this table.

TABLE 2.—*Properties of various woods, strength values at 15 per cent moisture, for use in airplane design.*

Common and botanical names.	Specific gravity based on volume and weight when oven-dry.		Weight at 15 per cent moisture.	Shrinkage from green to oven-dry condition.		Static bending.				Compression parallel to grain; maximum crushing strength.	Compression perpendicular to grain; fiber stress at elastic limit.	Shearing strength parallel to grain.	Hardness, side; load required to imbed 0.444-inch ball to one-half its diameter.
	Average.	Minimum permitted.		Radial.	Tangential.	Fiber stress at elastic limit.	Modulus of rupture.	Modulus of elasticity.	Work to maximum load.				
HARDWOODS.			*Lbs. per cu. ft.*	*Per cent.*	*Per cent.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*1,000 lbs. per sq. in.*	*Inch lbs. per cu. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs.*
Ash, commercial white (Fraxinus americana, Fraxinus lanceolata, Fraxinus quadrangulata)	0.62	0.56	40	4.5	7.1	7,700	12,700	1,500	14.2	6,000	1,300	1,750	1,150
Ash, black (Fraxinus nigra)	.53	.48	35	5.0	7.8	5,800	10,500	1,400	14.1	4,900	800	1,350	740
Basswood (Tilia americana)	.40	.36	25	6.6	9.3	4,700	7,200	1,300	6.4	3,800	400	880	340
Beech (Fagus atropunicea)	.66	.60	41	4.8	10.6	7,400	12,600	1,500	13.3	5,900	1,100	1,700	1,060
Birch (Betula lutea, lenta)	.67	.61	43	7.0	8.5	8,400	13,500	1,800	17.6	6,600	1,000	1,620	1,070
Cherry, black (Prunus serotina)	.53	.48	35	3.7	7.1	7,300	10,600	1,400	12.0	5,800	700	1,500	830
Cottonwood (Populus deltoides)	.43	.39	28	3.9	9.2	4,500	7,000	1,200	7.3	3,800	400	800	380
Elm, rock (Ulmus racemosa)	.66	.60	44	4.8	8.1	6,700	12,500	1,400	19.3	5,800	1,200	1,650	1,200
Gum, red (liquidambar styraciflua)	.53	.48	34	5.2	9.9	6,700	10,400	1,400	11.0	4,900	700	1,500	650
Hickory (true hickories) (Hicoria glabra, laciniosa, alba, ovata)	.81	.73	50	7.3	11.4	8,900	16,300	1,900	28.0	7,300	1,800	1,800	....
Mahogany (true) (Swietenia mahagoni)	.54	.50	36	3.5	4.2	7,000	10,000	1,300	9.1	5,500	1,000	1,420	860
Mahogany, African (Khaya senegalensis)	.50	.46	34	4.8	5.5	7,100	10,400	1,400	10.3	5,100	900	1,270	730
Maple, hard (Acer saccharum)	.66	.60	42	4.8	9.2	8,100	12,900	1,600	12.9	6,500	1,200	1,990	1,200
Oak, commercial white (Quercus alba, macrocarpa, minor, michauxii)	.72	.65	46	5.3	9.2	6,700	12,000	1,400	12.7	5,900	1,300	1,760	1,270
Poplar, yellow (Liriodendron tulipifera)	.42	.38	28	4.1	6.9	4,800	7,500	1,300	6.2	4,100	400	900	370
Walnut, black (Juglans nigra)	.56	.52	38	5.2	7.1	7,900	11,900	1,500	13.1	6,100	1,000	1,300	950
CONIFERS.													
Cedar, incense (Libocedrus decurrens)	.36	.32	26	3.3	3.7	4,900	7,100	1,000	6.0	4,300	600	850	430
Cedar, Port Orford (Chamaecyparis lawsoniana)	.47	.42	31	5.2	8.1	6,200	10,300	1,700	9.7	5,300	700	1,160	580
Cedar, western red (Thuja plicata)	.34	.31	23	2.5	5.1	4,200	6,400	1,000	5.5	4,000	400	790	300
Cedar, white (northern) (Thuja occidentalis)	.32	.29	22	2.1	4.9	4,200	5,800	750	5.1	3,400	350	800	300
Douglas fir (Pseudotsuga taxifolia)	.52	.47	34	5.0	7.9	6,800	9,700	1,780	7.2	6,000	750	1,020	580
Pine, sugar (Pinus lambertiana)	.39	.36	27	2.9	5.6	5,300	7,400	1,100	5.0	4,300	540	950	410
Pine, western white (Pinus monticola)	.45	.40	29	4.1	7.4	5,100	7,800	1,400	6.9	4,800	480	670	360
Pine, white (Pinus strobus)	.39	.36	27	2.2	5.9	5,100	7,400	1,200	6.1	4,500	530	850	380
Pine, Norway (Pinus resinosa)	.51	.46	33	4.6	7.2	7,900	10,900	1,700	6.1	6,100	720	1,150	540
Spruce, red, white, Sitka (Picea rubens, canadensis, sitchensis)	.41	.36	27	3.9	7.5	5,100	7,900	1,300	7.4	4,300	500	920	430
Cypress, bald (Taxodium distichum)	.47	.42	31	3.8	6.0	6,100	8,800	1,300	6.8	5,400	670	940	460

Since it is impractical to season test specimens to precisely 15 per cent moisture, it was necessary to compute the strength values given in table 2 at this moisture from test data obtained at slightly different moisture contents. The formulæ used in these computations are presented here as a matter of record.

M less than 8, $$D_{15}=\frac{4(AD-B)}{19-M}+B$$

M 8 to 10, $$D_{15}=\frac{5(AD-B)}{20-M}+B$$

M 10 to 11, $$D_{15}=\frac{6(AD-B)}{21-M}+B$$

M 11 to 12, $$D_{15}=\frac{7(AD-B)}{22-M}+B$$

D_{15} = Strength at 15 per cent, AD = air dry strength value, B = green strength value, M = per cent of moisture.

The factors to be applied, and consequently the exact stress to be used in design, of course, will depend largely on the conditions to which it is assumed the machine will be subjected in flight. If they are the most severe which the machine is ever expected to sustain while in flight, the working stresses can be relatively high. If, on the other hand, the assumed conditions are only moderately severe, the stresses must be made lower in order to take care of exceptional conditions which may occur. It must also be remembered that working stresses can not be safely based on average strength figures, but must be lowered to a value which will be safe for the weakest piece likely to be accepted.

NATURE OF LOADING.

The time of duration of a stress on a timber is a very great factor in the size of the stress which will cause failure. A continuously applied load greater in amount than the fiber stress at elastic limit as obtained by the ordinary static bending test will ultimately cause failure.

The fiber stress at elastic limit in static bending for the dry material is usually somewhat more than nine-sixteenths of the modulus of rupture, and in compression parallel to the grain the elastic limit is usually more than two-thirds of the maximum crushing strength. Timber loaded slightly below the elastic limit will gradually give to loads and ultimately assume greater deflections than those computed by using the ordinary modulus of elasticity figures. In impact tests where a weight is dropped on the stick and the stress lasts for only a small fraction of a second, the stick is found to bend practically twice as far to the elastic limit as in static tests where the elastic limit is reached in about two minutes. The elastic stress developed in the stick under the blow is greater than the maximum stress obtained in the static test.

TENSILE STRENGTH.

In general data on the tensile strength of wood are little needed, and consequently there is very little data available. The following table presents a few figures on the tensile strength of several species tested green.

TABLE 3.—*Strength of various woods in tension parallel to grain.*

[From tests of small clear specimens of green timber.]

Species.	Number tests averaged.	Number trees represented.	Moisture content.	Specific gravity.	Tension parallel to grain average.	Probable variation of individual from average.
			Per cent.		*Lbs. per sq. in.*	*Lbs. per sq. in.*
Mahogany, African	20	5	49.7	c 0.457	15,110	2,075
Mahogany, Central American	27	7	50.1	c .492	16,400	2,400
Maple, sugar	6	4	47.1	.550	14,900	....
Oak, northern white [a]	50	18	49.9	c .645	14,012	2,900
Cedar, Port Orford	59	9	35.0	.399	11,730	1,210
Douglas fir (1)	63	10	24.1	c .530	16,200	1,735
Douglas fir (2)	48	10	23.0	c .477	13,300	2,050
Fir, white	10	10	50.0	.369	7,972	1,400
Hemlock, western	7	2	39 to 98	.390	7,716	1,570
Pine, Norway	4	2	31.0	.401	9,760	....
Pine, white	42	9	41 to 86	.351	9,580	1,405
Pine, alligator [b]	5	3	34.5	.500	9,880	....
Redwood	13	5	40 to 155	.400	9,600	1,170

[a] Not identified as to species.
[b] Araucaria from Chile, South America.
[c] Specific gravity based on oven-dry weight and volume. Other specific gravities based on oven-dry weight and volume as tested.

(1) Specimens from the 8 feet immediately above stump. (2) Specimens from the fifth 8-foot bolt above stump and higher. (1) and (2) rom same trees.

TORSIONAL STRENGTH.

Resistance to torsion is important in connection with control surface spars. The following fragmentary data are based on only 30 tests in all, 15 of each species:

TABLE 4.—*Torsional strength of commercial white ash and Sitka spruce.*

Properties.	White ash.	Sitka spruce.
Number of tests	15	15
Moisture, per cent of oven-dry weight	15.8	15.7
Specific gravity (based on oven-dry weight and oven-dry volume)	.62	.39
Shearing strength at elastic limit, pounds per square inch	1,753	1,090
Shearing strength at maximum load, pounds per square inch	2,371	1,654
Shearing modulus of elasticity, pounds per square inch	88,500	72,300
Work to elastic limit, inch-pounds per cubic inch	8.8	4.4
Work to first failure, inch-pounds per cubic inch (*1*)	24.0	19.7

(*1*) For the spruce and ash tested the first failure occurred at maximum load in all cases.

SHRINKAGE.

Ordinarily when a piece of green lumber is dried no change in dimensions takes place until the fiber saturation point is reached. The wood then begins to shrink in cross-sectional area until no further moisture can be extracted from the cell walls. It also shrinks longitudinally, but in most cases the amount of longitudinal shrinkage is so small as to be negligible.

The shrinkage in cross-sectional area in drying from the green to the oven-dried condition varies with different woods, ranging from as much as 22 per cent (based on the original area before drying begins) to as little as 6 per cent. When dry wood absorbs moisture it continues to swell until the fiber saturation point is reached. Figures 18, 19, and 20 illustrate the progress of shrinkage and swelling between zero moisture content and the fiber saturation point.

The shrinkage of wood, like its strength, is very closely related to its specific gravity. This illustrated by figure 21. On this curve, "Per cent shrinkage in volume" is the total shrinkage from fiber saturation to dryness. It will be noted that shrinkage, in general, increases with specific gravity. This relation in individual specimens of a single species (white ash) is shown in figure 22.

Radial shrinkage, or the shrinkage in width of quarter sawn boards, averages about three-fifths as great as tangential shrinkage, or the shrinkage in width of flat sawn boards.

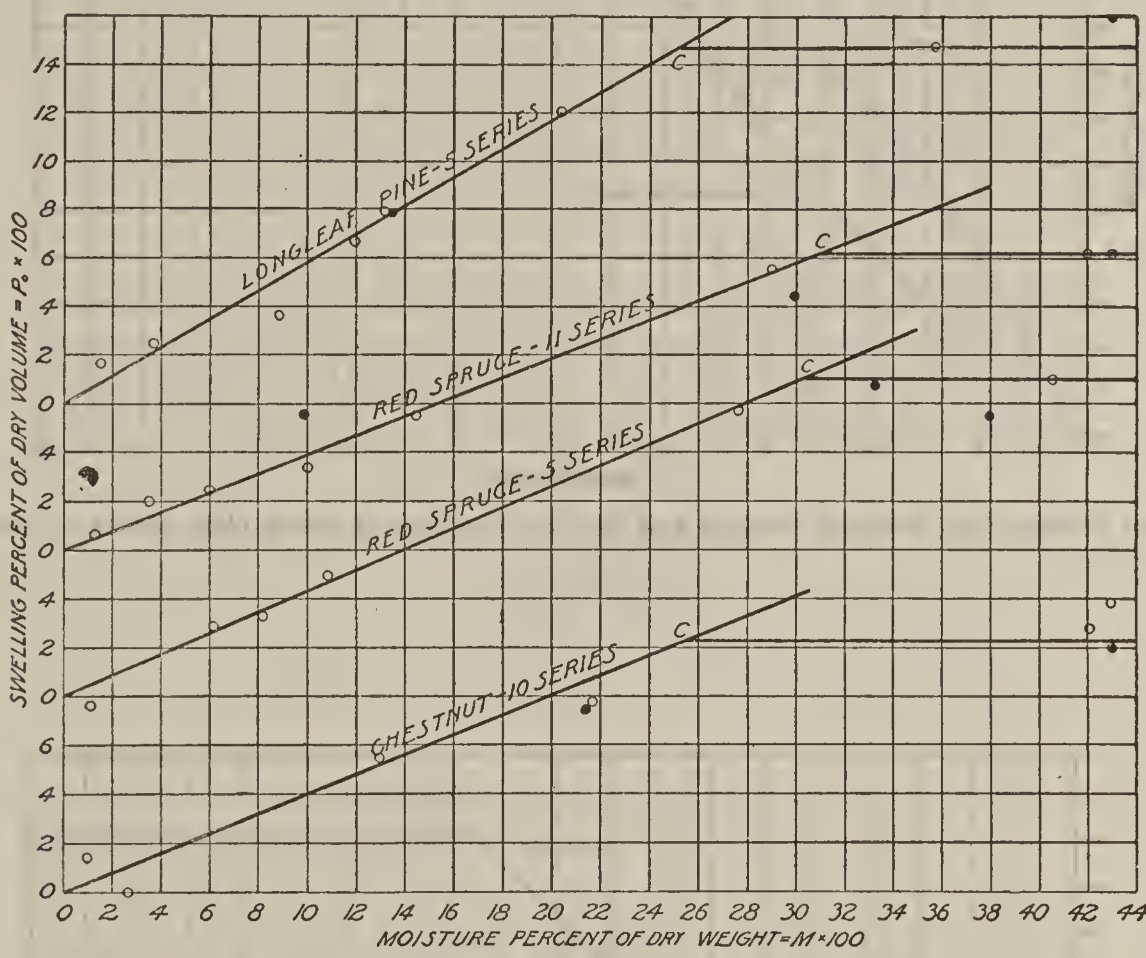

Fig. 18.—Relation between swelling and moisture. Each point is the average of from five to eleven specimens. Black dots indicate specimens that were kiln-dried and then allowed to reabsorb moisture. The fiber-saturation point is at c.

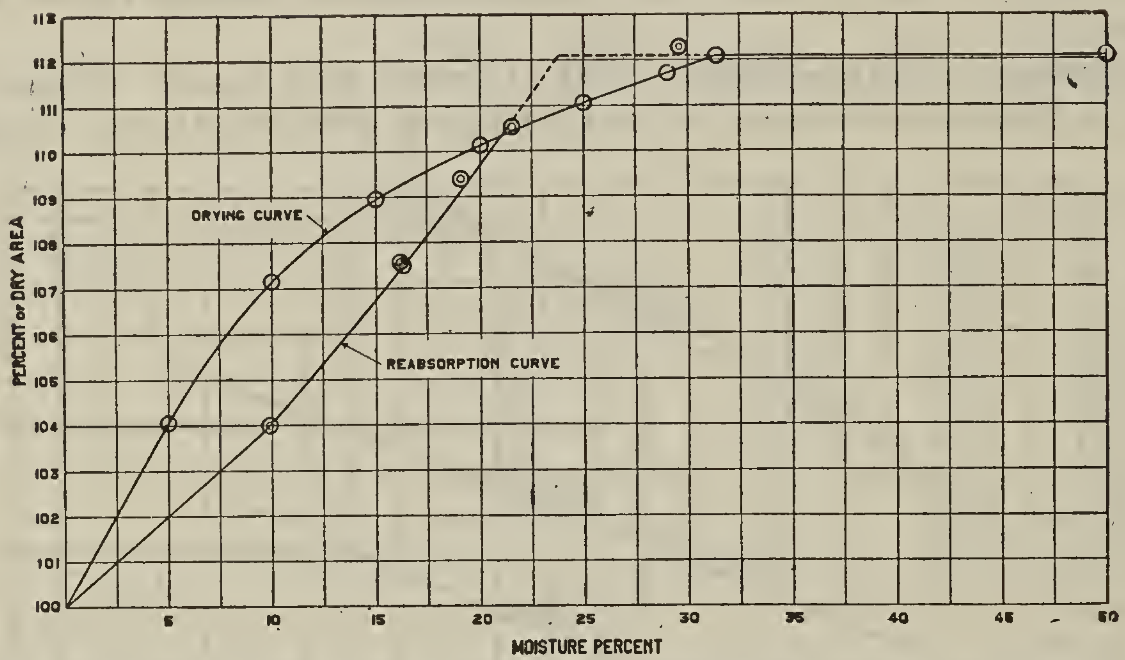

Fig. 19.—Relation between the moisture content and the cross section of small, clear pieces of western hemlock.

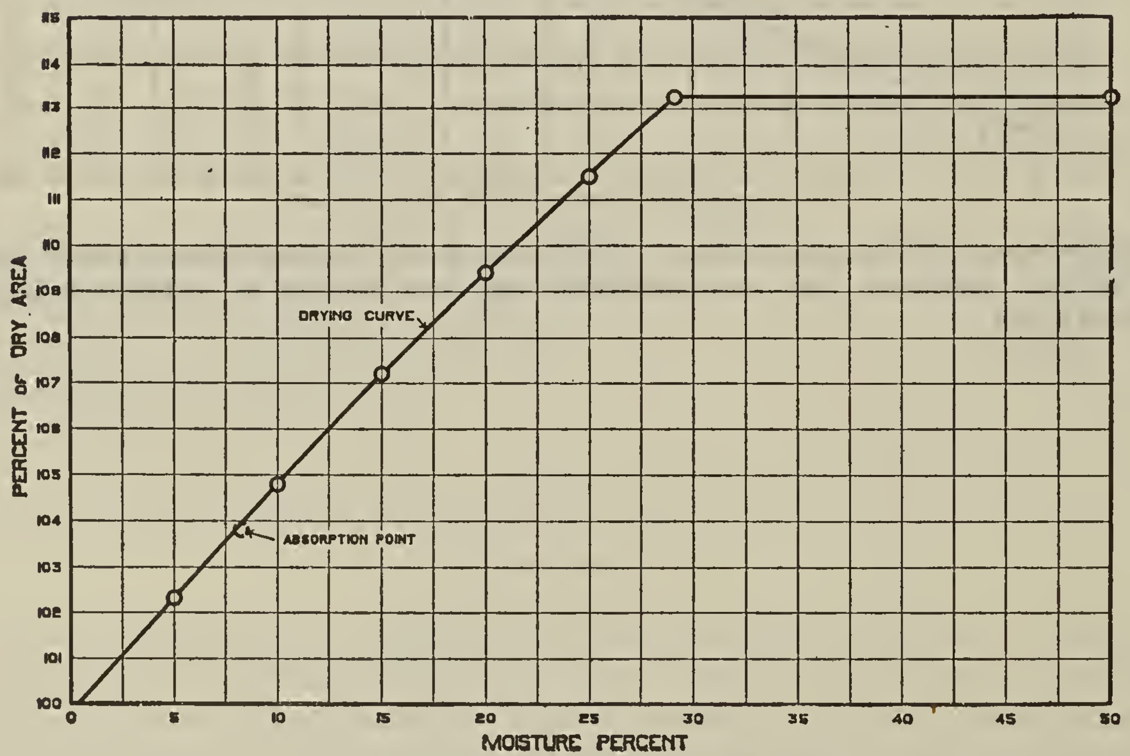

Fig. 20.—Relation between the moisture content and the cross section of small, clear specimens of western larch.

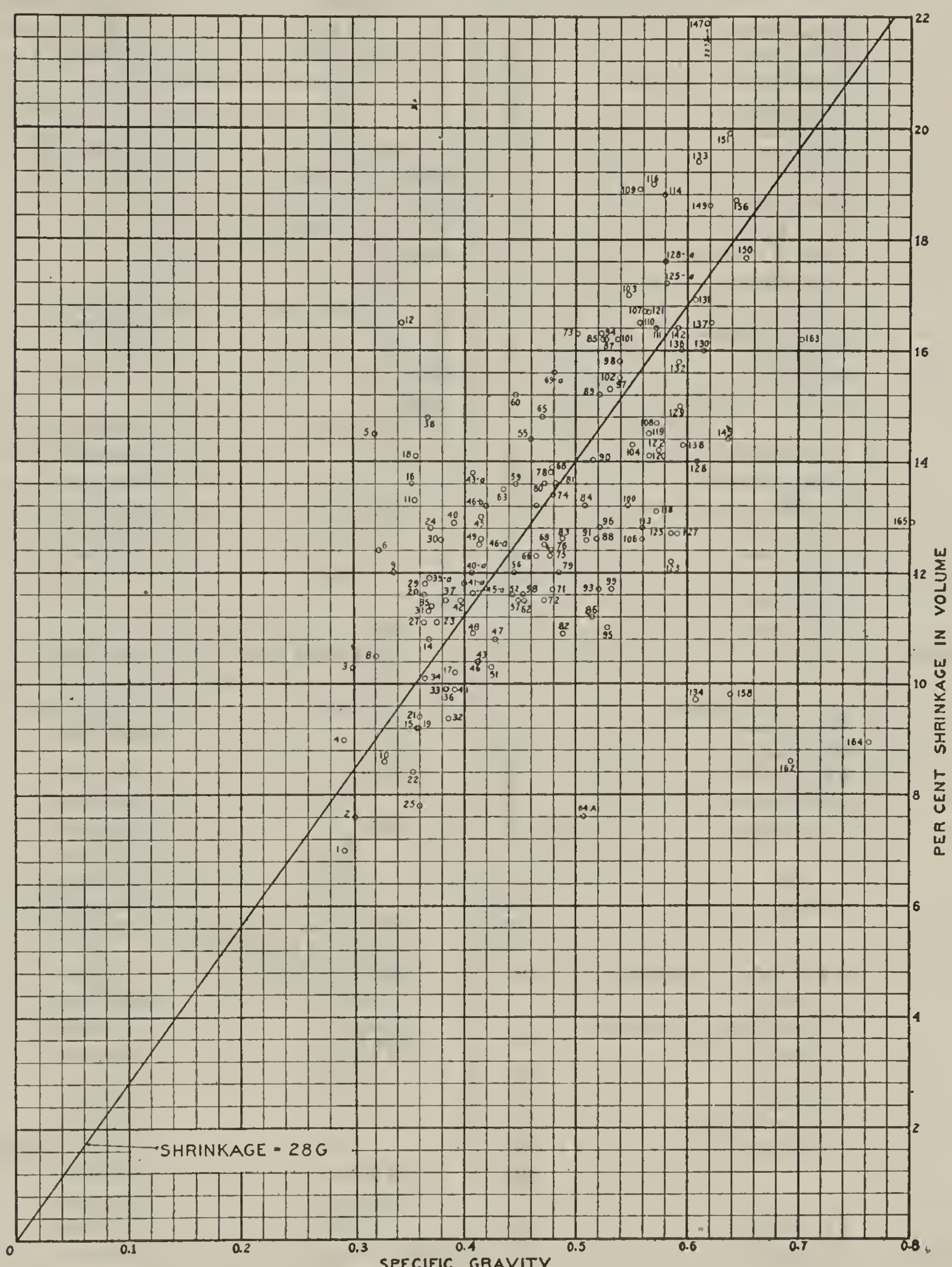

Fig. 21.—Relation between shrinkage in volume and specific gravity of various American woods.

List of species and reference numbers for figure 21.

HARDWOODS.

Species.	Locality.	Reference No.
Alder, red	Washington	30
Ash:		
Biltmore	Tennessee	91
Black	Michigan	60
Do	Wisconsin	70
Blue	Kentucky	99
Green	Louisiana	93
Do	Missouri	100
Pumpkin	do	79
White	Arkansas	106
Do	New York	128
Do	West Virginia	83
Aspen	Wisconsin	23
Largetooth	do	20
Basswood	Pennsylvania	12
Do	Wisconsin	5
Beech	Indiana	110
Do	Pennsylvania	98
Birch:		
Paper	Wisconsin	73
Sweet	Pennsylvania	129
Yellow	do	107
Do	Wisconsin	103
Buckeye, yellow	Tennessee	9
Buckthorn, cascara	Oregon	84a
Butternut	Tennessee	27
Do	Wisconsin	21
Chinquapin, western	Oregon	46b
Cherry:		
Black	Pennsylvania	72
Wild red	Tennessee	24
Chestnut	Maryland	46
Do	Tennessee	40
Cottonwood, black	Washington	6
Cucumber tree	Tennessee	59
Dogwood:		
Flowering	do	151
Western	Oregon	125a
Elder, pale	do	69a
Elm:		
Cork	Wisconsin, Marathon County.	126
Do	Wisconsin, Rusk County.	
Slippery	Indiana	102
Do	Wisconsin	74
White	Pennsylvania	55
Do	Wisconsin	53
Greenheart		165
Gum:		
Black	Tennessee	68
Blue (Eucalyptus)	California	147
Cotton	Louisiana	76
Red	Missouri	54
Hackberry	Indiana	90
Do	Wisconsin	78
Haw, pear	do	146
Hickory:		
Big shellbark	Mississippi	135
Do	Ohio	154
Butternut	do	139
Mockernut	Mississippi	144
Do	Pennsylvania	159
Do	West Virginia	155
Nutmeg	Mississippi	112
Pignut	do	148
Do	Ohio	157
Hickory—Continued.		
Pignut	Pennsylvania	160
Do	West Virginia	161
Shagbark	Mississippi	140
Do	Ohio	152
Do	Pennsylvania	143
Do	West Virginia	153
Water	Mississippi	141
Holly, American	Tennessee	87
Hornbeam	do	149
Laurel, mountain	do	145
Locust:		
Black	do	158
Honey	Indiana	162
Madrona	California	101
Do	Oregon	128a
Magnolia	Louisiana	66
Maple:		
Oregon	Washington	58
Red	Pennsylvania	69
Do	Wisconsin	92
Silver	do	56
Sugar	Indiana	104
Do	Pennsylvania	108
Do	Wisconsin	124
Oak:		
Bur	do	125
California black	California	80
Canyon live	do	163
Chestnut	Tennessee	121
Cow	Louisiana	133
Laurel	do	116
Post	Arkansas	130
Do	Louisiana	137
Red	Arkansas	119
Do	Indiana	118
Do	Louisiana	117
Do	Tennessee	97
Highland Spanish	Louisiana	94
Lowland Spanish	do	142
Swamp white	Indiana	150
Tanbark	California	115
Water	Louisiana	111
White	Arkansas	132
Do	Indiana	138
Do	Louisiana, Richland Parish.	136
Do	Louisiana, Winn Parish.	131
Willow	Louisiana	109
Yellow	Arkansas	122
Do	Wisconsin	105
Osage orange	Indiana	164
Poplar, yellow (tulip tree).	Tennessee	35
Rhododendron, great	do	85
Sassafras	do	51
Serviceberry	do	156
Silverbell tree	do	49
Sourwood	do	89
Sumac, staghorn	Wisconsin	61
Sycamore	Indiana	63
Do	Tennessee	65
Umbrella, Fraser	do	45
Willow:		
Black	Wisconsin	11
Western black	Oregon	43a
Witch hazel	Tennessee	114

List of species and reference numbers for figure 21—Continued.

CONIFERS.

Species.	Locality.	Reference No.	Species.	Locality.	Reference No.
Cedar:			Pine—Continued.		
Incense	California	26	Lodgepole	Montana, Granite County.	41a
Western red	Montana	2	Do	Montana, Jefferson County.	40a
Do	Washington	10	Do	Wyoming	34
White	Wisconsin	1	Longleaf	Florida	123
Cypress, bald	Louisiana	62	Do	Louisiana, Lake Charles.	113
Douglas fir	California	45a	Do	Louisiana, Tangipahoa Parish.	96
Do	Oregon	67a	Do	Mississippi	95
Do	Washington, Chehalis County.	46a	Norway	Wisconsin	57
Do	Washington, Lewis County.	75	Pitch	Tennessee	71
Do	Washington and Oregon.	67	Pond	Florida	86
Do	Wyoming	48	Shortleaf	Arkansas	77
Fir:			Sugar	California	22
Alpine	Colorado	4	Table Mountain	Tennessee	82
Amabilis	Oregon	39	Western white	Montana	42
Do	Washington	18	Western yellow	Arizona	19
Balsam	Wisconsin	14	Do	California	37
Grand	Montana	36	Do	Colorado	41
Noble	Oregon	16	Do	Montana	32
White	California	17	White	Wisconsin	25
Hemlock:			Redwood	California, Albion	28
Black	Montana	47	Do	California, Korbel	13
Eastern	Tennessee	52	Spruce:		
Do	Wisconsin	15	Engelmann	Colorado, Grand County.	8
Western	Washington	50	Do	Colorado, San Miguel County.	3
Larch, western	Montana	84	Red	New Hampshire	44
Do	Washington	64	Do	Tennessee	29
Pine:			White	New Hampshire	7
Cuban	Florida	127	Do	Wisconsin	38
Jack	Wisconsin	43	Tamarack	do	81
Jeffrey	California	33	Yew, western	Washington	134
Loblolly	Florida	88			
Lodgepole	Colorado	31			
Do	Montana, Gallatin County.	35a			

SUITABILITY OF VARIOUS AMERICAN WOODS FOR AIRCRAFT CONSTRUCTION.

The difficulty of securing ample supplies of the woods heretofore considered as the standards for aircraft construction has made it necessary to consider the substitution of other species. It must must be realized that aircraft can, if necessary, be made from practically any species of wood which will furnish material in the required sizes, and progress in laminating and splicing has done much to increase the utilization of smaller sized material. It must also be borne in mind that the differences in suitability are slight for a number of species and that high-grade stock of a species considered to be inferior may actually be better than lower grade stock of

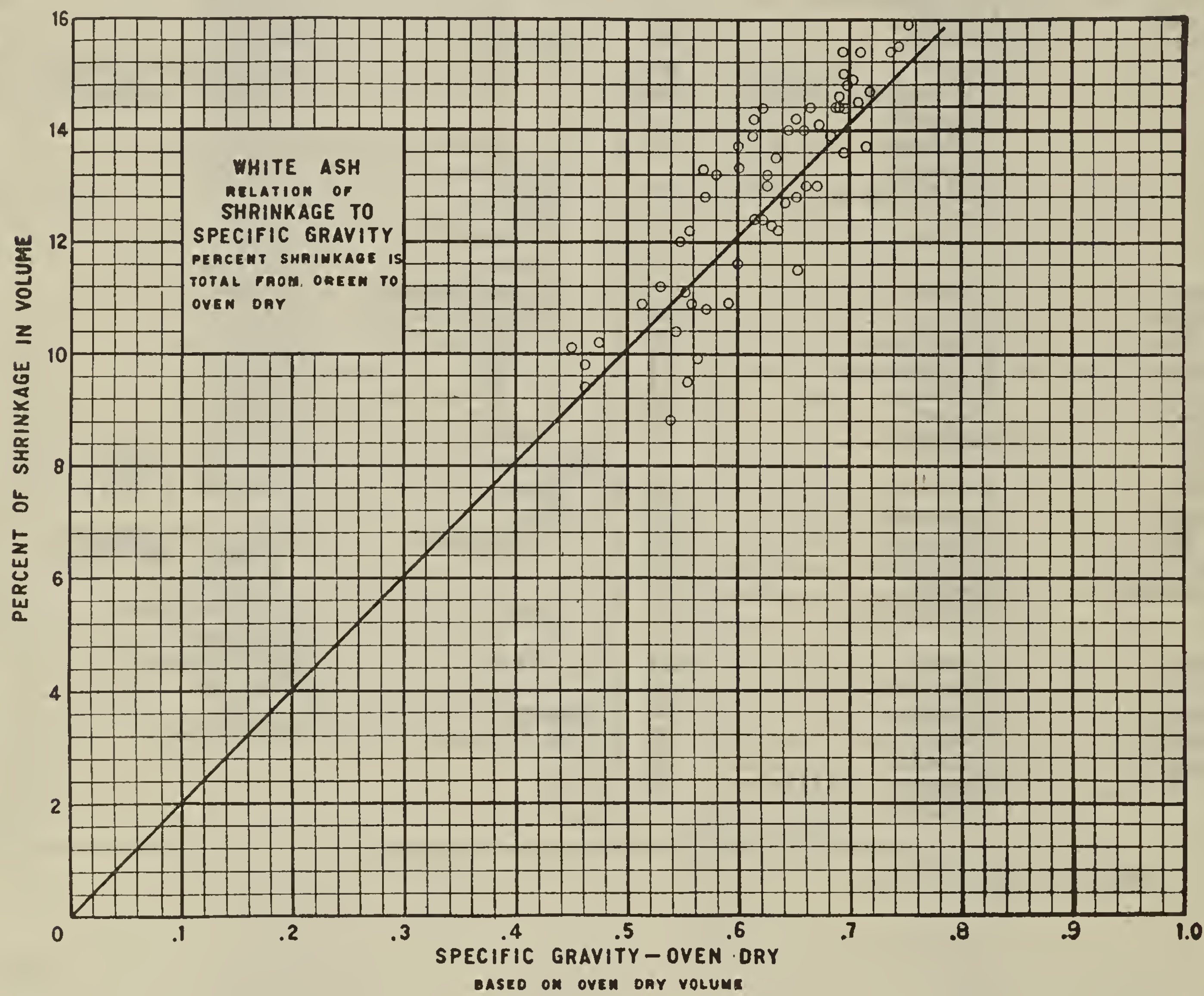

Figure 22.

the species considered superior. In other words, it may be preferable to change species and keep the grade up rather than to lower the grade and use the same species.

In order to give a general idea of the relative properties of the more common American species of timber, with respect to their use in aircraft, a short statement concerning each has been prepared. In those cases in which the species might possibly be considered as a substitute for spruce its properties are compared with those of spruce.

CONIFEROUS SPECIES.

Incense cedar.—This species is somewhat lighter than spruce, but lacks considerably in stiffness and does not possess the toughness of spruce. It might be substituted for spruce for parts which are not highly stressed.

Port Orford cedar.—Port Orford cedar is somewhat heavier than Sitka spruce and equals or exceeds it in all its strength properties. Recent data upon this species indicate that it is not as strong as originally supposed, but still show it to be equal to spruce, although of slightly greater weight.

Western red cedar.—Western red cedar is lighter than spruce and below it in all its strength properties. It is more difficult to dry, but could probably be used with success in many parts where spruce is now used, but could not be used in parts which are highly stressed.

White cedar.—White cedar is very low in all its strength properties. It is a comparatively small tree and could hardly be considered as a possibility for use for the larger members.

Bald cypress.—Bald cypress is slightly heavier than spruce. Its average figures show it somewhat superior to spruce when used in the same sizes. The great variability in the wood of this species has, however, prevented its recommendation for aircraft construction. Cypress is very wet in its green condition and is considered much more difficult to dry and glue than many other species.

Yellow cypress.—Data on this species are not very complete. The indications are that it is too low in stiffness to be a satisfactory substitute for spruce.

Douglas fir from the Pacific coast.—Douglas fir from the Pacific coast is considerably heavier than spruce and all its strength properties are equal to or exceed those of spruce. It is quite probable that the bulk of good wing-beam stock will come from second-cut logs and that the weight and corresponding strength values will run slightly lower than the average of the species. Douglas fir is considerably harder to dry than spruce and more inclined to shakes and to check during manufacture and to develop these defects in service. It is inclined to break in long splinters and to shatter when hit. The use of Douglas fir in the manufacture of wing beams requires considerably more care than is necessary with spruce, but it should give excellent results (from the strength standpoint) when substituted for spruce in the same sizes.

Douglas fir, Rocky Mountain type.—The Rocky Mountain type of Douglas fir is much smaller than the coast type, is quite knotty and somewhat brash, and probably would not be satisfactory as a substitute for spruce.

Alpine fir.—The Alpine fir so far tested was very low in weight and in all its strength properties. This material was from small knotty trees and should not be used except to resist low stresses. It is quite possible that the wood in more extensive stands of comparatively large Alpine fir will be heavier and stronger than that already tested.

Amabilis fir.—The amabilis fir so far tested was slightly heavier than spruce and in most of its strength properties it was practically the equal of spruce. Sufficient data are not at hand to determine how this material will kiln dry nor to determine its working properties. If it can be kiln dried and worked satisfactorily, indications are that it will be a fairly satisfactory substitute for spruce in spruce sizes in wing beams, struts, and other highly stressed parts.

Balsam fir.—Balsam fir is somewhat lighter than spruce and considerably lower in all its strength properties. It does not give promise of being satisfactory in airplane construction.

Grand fir, noble fir, and white fir.—The grand fir so far as tested was slightly heavier than spruce, while the noble and white fir were slightly lighter. In strength properties these species compare very favorably with spruce except in the case of the shock-resisting ability of white fir, which is a little low. This, however, may be accidental. The statement made concerning amabilis fir will apply to these species also.

Black hemlock.—Black hemlock is quite a little heavier than spruce and lacking in stiffness.

Eastern hemlock.—On a basis of strength properties alone eastern hemlock appears to be a substitute for spruce, but the lumber is shaky and liable to heart rot, has numerous knots, and develops shakes and checks in service. It need not, therefore, be considered.

Western hemlock.—Western hemlock is heavier than spruce, but not quite so heavy as Douglas fir. It is low in shock-resisting ability, but on a basis of strength alone it might serve as a substitute for spruce in spruce sizes. No data are available concerning proper kiln-drying methods and the possibility of manufacturing conditions which would cause this species to be rejected.

Western larch.—Butts of the western larch tree are very heavy. The material is shaky and is hard to dry. It would not seem feasible to use this species for aircraft in view of the supply of more suitable species.

Cuban pine.—Cuban pine is entirely too heavy to be considered.

Jack pine.—The jack pine so far tested was 9 per cent heavier than spruce and was lacking in stiffness.

Jeffrey pine.—Jeffrey pine is especially lacking in stiffness.

Loblolly pine.—Loblolly pine is quite heavy. It is very variable in its properties and need not now be considered.

Lodgepole pine.—Lodgepole pine is somewhat low in its shock-resisting ability and slightly low in stiffness. If extensive stands of large trees can be located, there is a possibility that it might be found practicable to use some of this species.

Longleaf pine.—This material is considered too heavy for use in airplanes without redesign.

Norway pine.—Indications are that Norway pine can be used as a substitute for spruce in spruce sizes. More data are needed as to kiln drying and the difficulties which may be met in manufacture.

Pitch and pond pine.—Pitch and pond pine are both heavy, and it is not likely that they would ever be needed in aircraft work.

Shortleaf pine.—The lighter material from the shortleaf pine could be used for aircraft construction, but probably would not be as satisfactory as Douglas fir, since weight for weight it shows a lower modulus of rupture and stiffness.

Sugar pine.—Sugar pine is quite low in shock-resisting ability and stiffness and is quite variable. It probably would not, therefore, be a suitable substitute for spruce.

Table mountain pine.—Table mountain pine has about the properties of shortleaf pine. It probably would not produce clear material satisfactory for aircraft stock.

Western white pine.—Western white pine is slightly heavier than spruce and shows up well in all its strength properties except hardness. It is more difficult to dry than the eastern white pine, but probably could be substituted for spruce in spruce sizes.

Western yellow pine.—Strength data show the western yellow pine to be lacking in shock-resisting ability and stiffness. It is also quite variable. It is not considered a good substitute for spruce.

Eastern white pine.—Tests to date show eastern white pine somewhat below spruce in hardness and rather low in shock-resisting ability. It, however, runs quite uniform in its strength properties, is very easily kiln dried without damage, works well, stays in place well, and is recommended for aircraft construction as a substitute for spruce in spruce sizes.

Redwood.—The data available on redwood are not comparable to those on other species and are too erratic to form a very definite judgment of the species. The indications are that the material is quite variable in its properties and likely to be very brash.

Engelmann spruce.—Engelmann spruce is quite light and low in all its strength properties.

Tamarack.—Tamarack is too heavy to be substituted for spruce. It probably would not furnish clear material.

Yew.—This wood is very heavy. The tree is small and crooked.

HARDWOODS.

Red alder.—Data on this species are very meager, but it is probably not available in sizes sufficiently large to make it of importance.

Biltmore ash.—Biltmore ash should be considered along with white ash and may be used for longerons and other work where strength, stiffness, and ability to steam bend are of importance.

Black ash.—Black ash is very low in stiffness. It is an exceedingly tough species. It is one of the best native species for steam bending. It can not be used, however, where strength and stiffness are of great importance, as in places where white ash is used.

Blue, green, and white ash.—These species are known commercially as white ash and are very desirable for use in longerons and other places where steam bending, great strength, and stiffness are required.

Oregon ash.—Oregon ash appears to be about equal to the eastern white ash, although the data on this species are somewhat meager.

Pumpkin ash.—Pumpkin ash as a species is somewhat lighter than the white ashes. It is considerably less stiff than the white ash. Commercially the term is made to include the weak, soft material from all the other species of ash.

Commercial white ash.—Commercial white ash includes the Biltmore, blue, green, and white ash already mentioned.

Aspen.—Aspen is quite soft and lacking in stiffness.

Basswood.—Basswood is light in weight and low in practically all its strength properties. It is one of the best species to receive nails without splitting and is used extensively for webs, veneer cores, and similar work.

Beech.—Beech is quite heavy and has about the strength properties of sweet and yellow birch and hard or sugar maple. It might be used to some extent in propellers but not extensively in other aircraft parts.

Paper birch.—Paper birch is rather low in its stiffness and high in weight.

Sweet and yellow birch.—Sweet and yellow birch are quite heavy, hard, and stiff. They have a uniform texture and take a fine finish. On account of their hardness and resistance to wear they can be used to face other woods to protect them against abrasion.

Yellow buckeye.—Yellow buckeye is low in its weight and all its strength properties.

Cascara buckthorn.—Cascara buckthorn is a small tree and need not be considered.

Butternut.—Butternut is lacking in stiffness and probably need not be considered.

Western chinquapin.—Western chinquapin is a small tree and need not be considered.

Black cherry.—Black cherry is a very desirable propeller wood.

Wild cherry.—Wild cherry is a small tree and lacking in stiffness.

Chestnut.—Chestnut is somewhat heavier than spruce and is quite deficient in stiffness.

Cottonwood.—The cottonwood so far tested was slightly heavier than spruce. It is soft, low in its strength as a beam or post, and lacks stiffness. It is very tough, however, does not split in nailing, and bends well. Cottonwood can not well be substituted for spruce in wing beams and long struts but can be used in minor parts.

Black cottonwood.—Black cottonwood is low in weight and all its strength properties.

Cucumber tree.—The wood of the cucumber tree is somewhat heavier than spruce and shows up well in all its strength properties. It is one of the few hardwoods which gives promise of being a good substitute for spruce in wing beams and struts.

Flowering and western dogwood.—The dogwood trees are too small to be considered.

Elder, pale.—Elder is too small a tree to be considered.

Elm, cork (rock elm).—Cork elm is slightly heavier than ash. It is low in stiffness and very resistant to shocks. It steam bends well and if properly dried can be used for longerons as a substitute for ash. Considerably more care is necessary in the drying of elm in order to have it remain in shape as it twists and warps badly when not held firmly.

Slippery elm.—Slippery elm is somewhat lighter than cork elm, but when of equal density may be used as cork elm.

White elm.—Very dense pieces of white elm have the requisite density and strength to be used along with cork elm. Most of the white elm, however, is quite light. It is lacking in stiffness, but steam bends well. It could probably be used to excellent advantage in the bent work at the ends of the wings, rudders, elevators, etc. Considerable care would be necessary in order to hold this material in place while drying, as it warps badly.

Black gum.—Black gum is considerably heavier than spruce and not nearly so stiff. It probably will be but little used in aircraft.

Blue gum (eucalyptus).—Eucalyptus grown in this country is quite heavy. It has large internal stresses, swells and shrinks excessively, twists badly in drying, and is very difficult to dry. Under present conditions it probably should not be used in aircraft.

Cotton gum (Tupelo).—This species is considerably heavier than spruce, but not nearly so stiff. At present it probably should not be considered for aircraft.

Red gum.—Red gum is considerably heavier than spruce and superior to it in strength properties. On account of its locked grain and its tendency to twist, warp, and check it probably should not be used in place of spruce. There is some prospect, however, that carefully quarter-sawed material of this species can be used in propellers.

Hackberry.—The denser pieces of hackberry might be substituted for ash in longerons.

Pear haw.—Pear haw is a very small tree and of no importance in this connection.

True hickories, including shellbark, mockernut, pignut, and shagbark.—These species are heavier than ash and are very tough and strong. They could be substituted for ash in longerons, but would probably not give quite as good service for the same weight.

Pecan hickories, including butternut, nutmeg, pecan, water.—These hickories are considerably inferior to the true hickories, especially in their ability to resist shock, and probably would not make satisfactory substitutes for ash.

American holly.—This species is lacking in stiffness and probably is of no importance in airplane construction.

Hornbeam, California laurel, mountain laurel, black locust, honey locust, madrona.—The laurels, locusts, and madrona are all heavy woods and probably have little use in aircraft construction.

Magnolia.—Magnolia has approximately the same properties as cucumber wood, to which it is closely related, and could probably be used as a substitute for spruce in wing beams and longerons.

Oregon maple.—Oregon maple has about the same properties as silver maple. It is a little more stiff and not quite so resistant to shock. There is probably little use for either of these species in aircraft.

Red maple.—Red maple is somewhat heavier, stiffer, and stronger than silver maple. Red maple might possibly be used in propeller work, but would give much softer propellers than sugar maple.

Sugar maple.—Sugar maple is quite heavy, hard, and stiff. It could be used with birch in propeller manufacture. It has very uniform texture and takes a fine finish. On account of its hardness and resistance to wear it is very often used to face other woods to protect them against abrasion.

Silver maple.—Silver maple is the lightest and softest of all the maples. It is much too soft to be considered as a substitute for sugar maple and lacks the stiffness to make it a satisfactory substitute for spruce.

The oaks.—The oaks need not be considered as substitutes for spruce, but they play an important part in the manufacture of propellers. The oaks are all quite heavy and hard. The oaks, even when a single botanical species is considered, are extremely variable in their strength properties. The differences in the average strength properties of the various eastern oaks are not great, and greater differences might readily be found among different logs of any one species. The white oaks, as a rule, shrink and swell more slowly with changes in the weather than do the red oaks. The radial shrinkage of the oaks is about one-half the tangential shrinkage. This accounts for the much greater value of quarter-sawed oak over plain-sawed oak for propeller construction. The southern-grown oaks are much more difficult to dry than are the northern oaks. Experiments are being made in the drying of both northern and southern red and white oaks. The northern white oaks when quarter-sawed and carefully dried make very satisfactory propellers. It is possible that quarter-sawed northern red oak will also make fairly satisfactory propellers but with this disadvantage: It is more subject to defects in the living tree, decays more readily, and changes more rapidly with changes in weather conditions. To be satisfactory in this work the southern oaks will require exceeding care in drying, as they are very difficult to dry without checking, honeycombing, and casehardening.

Osage orange, persimmon.—Osage orange and persimmon have other very important uses and are probably of no importance in aircraft construction.

Yellow poplar.—Yellow poplar is but little heavier than spruce, and while rather low in shock-resisting ability has good working qualities, retains its shape well, is comparatively free from checks, shakes, and such defects. It would probably be a fairly satisfactory substitute for spruce in wing beams and struts. It offers no manufacturing difficulties.

Rhododendron, sassafras, service berry, silverbell, sourwood, sumac.—These species probably have no place in aircraft construction.

Sugarberry.—This species is closely related to the hackberry and the denser pieces might be substituted for ash in longeron construction.

Sycamore.—The trees are very shaky and probably would not furnish material suitable for aircraft.

Fraser umbrella.—This species is closely related to the cucumber and magnolia previously discussed and has similar properties. The clear stock obtained might be used as a substitute for spruce.

Willow, black and western black, witch hazel.—Willow and hazel probably are of no use in aircraft construction.

Walnut, black.—Black walnut has many very important uses and need not be considered as a substitute for spruce. This species probably makes the best propellers of any of the native species. It is somewhat difficult to dry, but stays in place unusually well and is hard enough to resist wear.

SYNOPSIS OF COMMENTS AS TO SUBSTITUTES FOR SPRUCE.

The following species range in weight from that of spruce to 25 per cent heavier than spruce. The data available indicate strongly that these species can be substituted for spruce in highly stressed parts using the spruce design: Port Orford cedar, coast type Douglas fir, eastern and western white pine, yellow poplar, cucumber tree and magnolia. The following species give promise of furnishing substitutes for spruce, but more experiments are needed in order to overcome known difficulties before these species can be recommended: Bald cypress, amabilis fir,

grand fir, noble fir, white fir, lodgepole pine, Norway pine, and redwood. The following species are lighter than spruce, but could be used in parts where the stresses are relatively low: Incense cedar, western red cedar, and Alpine fir.

As conditions change other species will doubtless come into consideration as substitutes for spruce.

STORAGE AND KILN DRYING OF LUMBER.

The proper piling of lumber and timber for air seasoning or as temporary storage previous to kiln drying is extremely important. Green or partially dry stock is subject to various forms of deterioration, such as staining, decay, severe checking, and (especially in hardwoods) insect attack. During warm, humid weather staining may take place in a few days and decay may weaken the wood in a few months.

Proper piling of such stock will tend to reduce the deterioration to a minimum. All lumber or timber which is to be stored any length of time should be piled on solid foundations with stickers between each two courses, and should have some protection from the sun and rain. Whenever possible, the stock should be piled in a shed with open sides. If this is not practicable, each pile should be covered so as to keep out rain and snow. Green hardwoods, especially oak, frequently check severely at the ends. This can be avoided to a large extent by coating the ends with linseed-oil paint.

Stock should be cut up into as small sizes as is practicable before kiln drying. Large pieces usually check severely because the outer portion dries and shrinks considerably faster than the inner core, which always dries slowly. Timbers which contain the pith and which are to be cut into smaller sizes later should at least be cut through the pith once, or, better, be quartered before being stored away. This will avoid the large checks which are commonly produced in the seasoning of timbers containing the pith by reason of the tangential shrinkage being greater than the radial shrinkage.

RULES FOR PILING LUMBER.

1. The foundations should be strong, solid, and durable, preferably concrete piers with inverted rails or I beams for skids. If this is impracticable, creosoted or naturally durable wooden timbers should be used.
2. Each foundation should be level.
3. The foundations should not be over 4 feet apart for lumber, but may be farther apart for larger timbers. For woods which warp easily or for stock less than 1 inch in thickness foundations should not be over 3 feet apart.
4. If the piles are in the open, they should have a slope from front to rear of 1 inch for every foot in length.
5. The foundations should be sufficiently high to allow the free circulation of air underneath the piles, and weeds or other obstructions to circulation should be removed.
6. Boards of equal length should be piled together with no free unsupported ends.
7. A space of about three-fourths of an inch should be left between boards of each layer and from 1 to 2 inches between timbers of each layer.
8. The stickers should be of uniform thickness, preferably seven-eighths of an inch for 1-inch lumber and $1\frac{1}{2}$ inches for thicker stock.
9. Stickers should be placed immediately over the foundation beams and kept in vertical alignment throughout the piles. Their length should be slightly in excess of the width of the pile.
10. The front and rear stickers should be flush with or protrude slightly beyond the ends of the boards.

KILN DRYING OF WOOD.

ADVANTAGES OF KILN DRYING.

The chief objects of kiln-drying airplane stock are (*a*) to eliminate most of the moisture in green or partly dried stock more quickly than can be done in air drying and (*b*) to reduce the moisture content of the wood below that attained in ordinary air drying, so that no more drying, with consequent checking, warping, and opening up of seams will occur after the wood is in place. Other advantages incident to kiln drying are that a smoother surface can be obtained on kiln-dried stock and that glues will hold better.

THE ELIMINATION OF MOISTURE FROM WOOD.

Green lumber may contain from about one-third to two and one-half times its oven-dry weight of water. Expressed in percentage, this is from $33\frac{1}{3}$ to 250 per cent moisture based on the oven-dry weight. The moisture content of green lumber varies with the species, the position in the tree, whether heartwood or sapwood, the locality in which the tree grew, and the drying which has taken place since the tree was cut. As a rule sapwood contains more moisture than heartwood, although in some species, especially in butt logs, the heartwood contains as much moisture as the sapwood. Thoroughly air-dried lumber may contain from about 10 to 20 per cent moisture for inch stock and more for thicker material.

Much of the moisture in green wood is contained in the cell cavities (like honey in a comb), and the rest is absorbed by the cell walls. When wood is drying the moisture first leaves the cell cavities and travels along the cell walls to the surface, where it is evaporated. When the cell cavities are empty but the cell walls are still saturated a critical point is reached, known as the fiber-saturation point. Wood does not shrink or increase in strength while seasoning until it has dried below the fiber-saturation point, which usually ranges between 25 and 30 per cent moisture, but may be less or more, and in spruce usually is between 30 and 35 per cent. This has an important bearing on the drying operation, since no casehardening, checking, or warping can occur so long as the moisture content is above the fiber-saturation point in all parts of the stick.

In practice the stock should be dried to a moisture content slightly less than it will ultimately have when in use. This may be as low as 6 per cent for interior work and not so low for wood to be exposed to weather.

Two steps are necessary in the drying of lumber—(*a*) the evaporation of moisture from the surface, and (*b*) the passage of moisture from the interior to the surface. Heat hastens both these processes. For quick drying as high a temperature should be maintained in the kiln as the wood will endure without injury. Some woods (especially coniferous woods) will endure higher temperatures than others. The general specifications for kiln-drying airplane stock which follow give the temperatures at which a kiln should be operated to prevent injury to lumber to be used for airplanes.

The lumber in a kiln is heated and evaporation is caused by means of hot air passing through the piles. To insure proper drying throughout the piles a thorough circulation of air is necessary. The lumber must be properly piled and the kiln constructed so as to make the necessary circulation possible.

Dry hot air will evaporate the moisture from the surface more rapidly than it can pass from the interior to the surface, thus producing uneven drying, with consequent damaging results. To prevent excessive evaporation and at the same time keep the lumber heated through, the air circulating through the piles must not be too dry; that is, it must have a certain humidity. The specifications give the proper humidities at which to operate the kiln for drying airplane stock.

THREE ESSENTIAL QUALITIES OF A DRY KILN.

The merits of any method of drying airplane woods depend upon the extent to which it affects the mechanical properties of the stock and upon the uniformity of the drying. In order that complete retention of properties and uniform drying may be guaranteed, it is essential that the circulation, temperature, and humidity of the air be adequately controlled. In this connection circulation does not mean the passage of air through flues, ducts, or chimneys, but through the piles of lumber, and the terms temperature and humidity control apply to the air within the piles of lumber in the kiln.

Control of air circulation involves rate or speed and uniformity. A uniform passage of air through all portions of the piles of lumber is the most essential quality in a kiln. If the circulation can be made both uniform and rapid, all portions of the pile will dry quickly and at the same rate. Furthermore, uniform and rapid circulation of air are necessary before the control of temperature and humidity within the piles of lumber is possible.

When unsaturated air at any given temperature enters a pile of lumber containing moisture, it exchanges heat for moisture, is cooled, and rapidly approaches saturation. With green wood and a sluggish circulation, the cooling is very rapid. The rate of cooling decreases as the lumber dries, and if the circulation is increased the loss of heat in passing through the pile is less. So if the air moves rapidly through certain parts of the piles and slowly through others, the different parts of the piles will be at different temperatures. The temperature of the air within the lumber can not be maintained at any given value unless the circulation of air is uniform at all points in the pile. Even though the air moves at uniform speed from one side of a pile of lumber to the other, if the speed is too slow the air loses its heat and approaches saturation rapidly. In general a wide variation in the temperature of the lumber in different parts of the kiln is proof of very uneven or slow circulation. Inadequate circulation and temperature control render the control of humidity and uniform drying impossible.

Humidity is of prime importance, because the rate of drying and the prevention of checking and casehardening are directly dependent thereon. It is generally true that the surface of the wood should not dry more rapidly than the moisture transfuses from the center to the surface. The rate of evaporation must be controlled, and this can be done by means of the relative humidity. Stopping the circulation to obtain a high humidity or increasing the circulation by opening ventilators to reduce the humidity is not good practice. Humidity should be raised, if necessary, to check evaporation without reducing the circulation.

DEFECTS DUE TO IMPROPER DRYING.

Casehardening and honeycombing.—When the surface of a piece of lumber is dried more rapidly than the moisture can pass to it from the interior, unequal moisture conditions exist in the lumber. The moisture in the outer layers falls below the fiber saturation point. The outer layers then tend to shrink but are held from shrinking by the more moist interior, which has not yet started to shrink; so the surface either checks or dries in a stretched condition, usually both. Later, as the interior dries it also tends to shrink normally, but in turn is held by the outside, which has become "set" or "casehardened." Consequently, the interior dries under tension, which draws the outer layers together, closing up all checks and producing compression. Casehardened lumber, when resawed, will invariably cup toward the inside if the interior if the lumber is dry (fig. 23). If the tension in the interior of the wood is severe enough, it may produce radial checks which do not extend to the surface. Wood with such checks is said to be honeycombed or hollow-horned (fig. 24). Casehardening and honeycombing can practically be prevented by regulating the humidity so that the evaporation from the surface does not take place too rapidly.

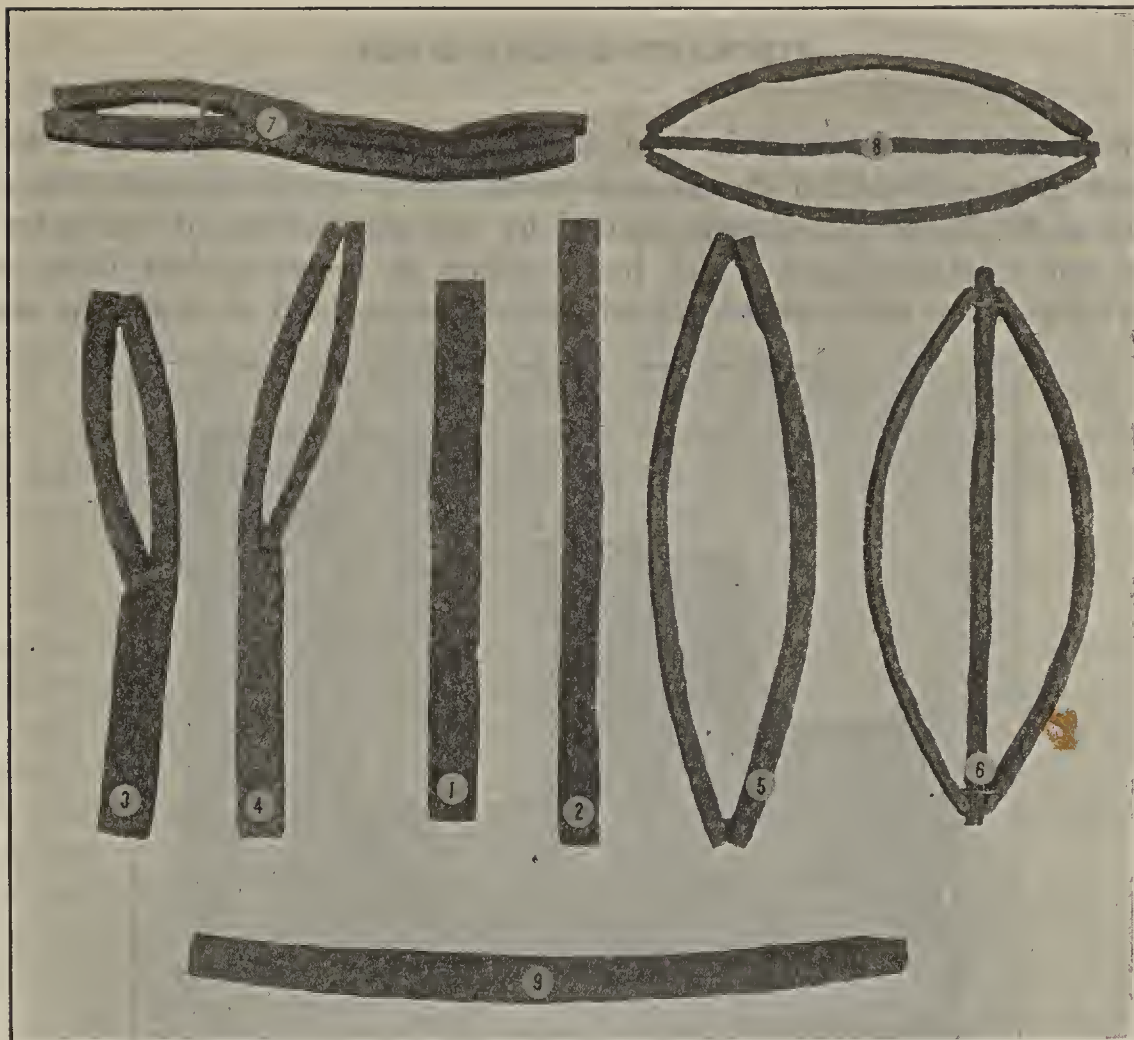

Fig. 23.—Sections of casehardened western larch boards. Nos. 1 and 2 are original sections; Nos. 3 to 8 are resawed sections showing cupping; No. 9 is one-side surfaced.

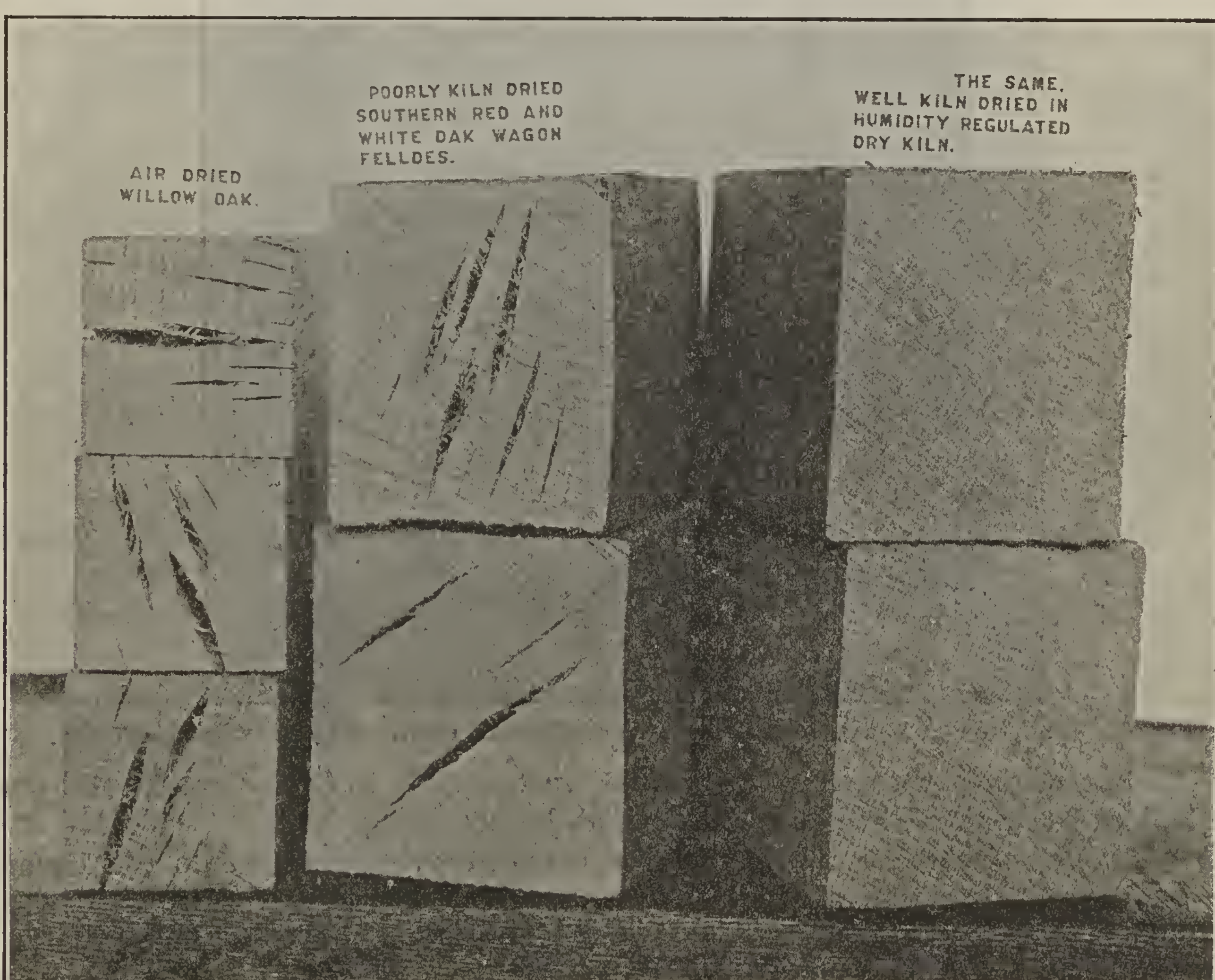

Fig. 24.—Oak stock honeycombed by air drying and improper kiln drying. Also similar stock properly dried.

If wood becomes casehardened in kiln drying, it may be brought back to normal condition by steaming, provided that checks and cracks have not developed. Steaming softens the outer fibers and relieves the stresses caused by the contraction of the outer shell. Care must be taken not to steam wood which has checked or honeycombed from casehardening enought to part the fibers and weaken the piece. Steaming will close up the cracks but will

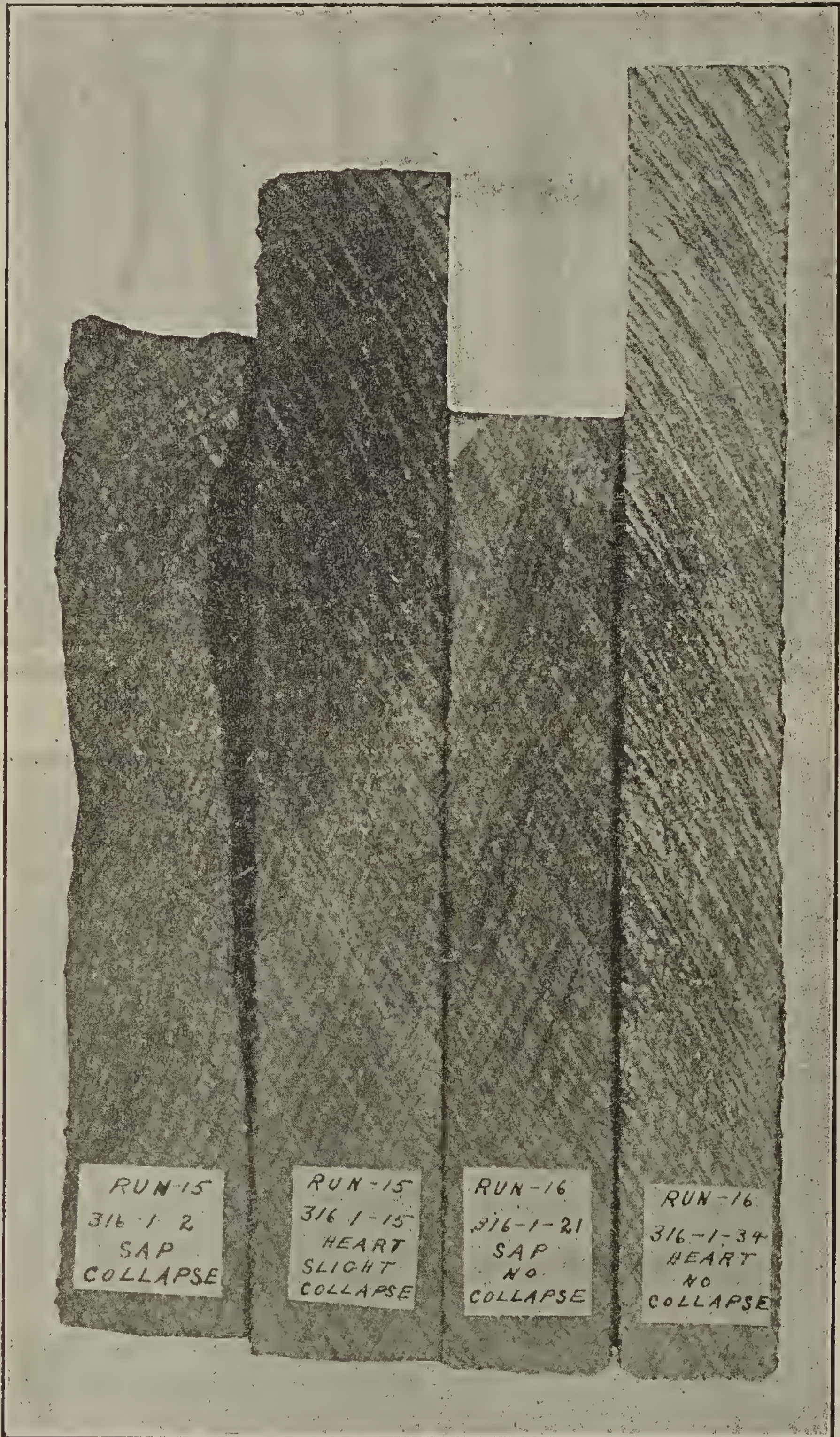

Fig. 25.—End view of 1-inch boards of western red cedar dried with and without collapse.

not restore the strength of the piece. It will be much harder to detect cracks and checks due to casehardening if they have been closed up again by steaming.

Collapse.—Collapse is abnormal shrinkage causing grooves to appear in the surface of the lumber or a genaral distortion of the surface (fig. 25). It is produced when wet lumber is dried at too high a temperature. The heat and moisture cause the cell walls to become soft and plastic. As the water leaves the cell cavities the moist cell walls are drawn together if no air is present. This causes the cells to flatten, and a general reduction in the cross sec-

tion takes place. Collapse occurs especially in such woods as western red cedar, redwood, white oak, and others which readily become soft and plastic when hot and moist. It can be avoided by not allowing the temperature to rise too high while the wood is still moist (at or above the fiber saturation point).

Brashness.—High temperature treatments of all kinds, whether steam or hot air, are injurious to lumber, causing it to turn darker and become brash. The injuries thus sustained increase with the temperature and length of time the wood is exposed to such severe conditions. No definite rule can be laid down as to what conditions of temperature wood will endure without becoming brash. If the temperatures prescribed in the specifications (see p. 68) are not exceeded, no difficulty will be experienced in this respect.

METHODS OF TESTING CONDITIONS DURING DRYING.

In drying airplane stock it is advisable to test conditions in the kiln at frequent intervals so that the operator will be able to make any changes promptly that the tests indicate are necessary to maintain the proper rate of drying and to prevent injury to the lumber. A continuous record of proper conditions during kiln drying is a strong assurance of satisfactory stock. The following tests will aid the inspector in keeping check on drying conditions.

1. Preliminary test:
    - (*a*) Initial moisture conditions in the lumber.
    - (*b*) Preparation and placing of samples.
    - (*c*) Initial weights and placing of whole pieces.
    - (*d*) Determination of direction, uniformity, and rate of air circulation.
    - (*e*) Location and calibration of instruments.
2. Current tests:
    - (*a*) Determination of current temperatures.
    - (*b*) Determination of current humidities.
    - (*c*) Determination of circulation.
    - (*d*) Weighing of samples and determination of current moisture conditions.
3. Final tests:
    - (*a*) Average kiln-dry moisture condition of samples.
    - (*b*) Distribution of moisture in the kiln-dry samples.
    - (*c*) Determination of casehardening in kiln-dry samples.
    - (*d*) Average kiln-dry moisture condition of whole pieces.
    - (*e*) Calculation of initial moisture condition of whole pieces.
    - (*f*) Distribution of moisture in kiln-dry whole pieces.
    - (*g*) Distribution of casehardening in kiln-dry whole pieces.
    - (*h*) Determining the effect of the process on the toughness and strength of the kiln-dry stock.

In making these tests the following instruments and material will be needed:

1 sensitive equal arm balance (capacity, 0.1 to 250 grams).
1 drying oven in which the air can be heated to and held at 212° F.
1 can of asphalt paint and a brush.
1 sensitive platform scale (capacity, 0.01 to 250 pounds).
1 electric flash light (lantern type recommended).
12 packages of punk sticks.
3 accurate standardized ordinary glass thermometers (60° to 230° F. by 2° intervals).
2 accurate standardized glass wet and dry bulb hygrometers with extra wicks (60° to 230° F. by 2° intervals).
Access to a laboratory equipped with machines for making impact, static bending, hardness, compression parallel to the grain, and other tests.
Waxed or oiled paper.

1. *Preliminary tests.*—(*a*) Initial moisture condition: Select at least three representative pieces for each 10,000 board feet of stock to be dried. Cut about 2 feet from one end of each. Then cut a 1-inch section, a 24-inch sample, and a second 1-inch section in succession. Immediately weigh the two 1-inch sections to an accuracy of one-tenth of 1 per cent. Mark the initial weights on the section and dry them to constant weight in the oven heated to 212° F. Reweigh them to the same accuracy and determine the per cent initial moisture content of the samples from the formulæ:

$$\text{Per cent initial moisture content} = \frac{\text{Initial weight—oven-dry weight}}{\text{oven-dry weight}} \times 100$$

(*b*) Preparation and placing of samples: Immediately after cutting the 24-inch samples described under (*a*) paint the ends of the samples with a heavy coat of asphalt paint. Then weigh them separately on the platform to an accuracy of one-tenth of 1 per cent. Mark the initial weights on the samples and place them in the piles so as to come under the most severe, least severe, and average drying conditions, and so as to be subjected to the same drying conditions as the adjacent pieces. Where the circulation of air is vertical, place samples near the tops, centers, and bottoms of the piles, and where the circulation is lateral place them near the sides where the air enters and leaves the piles and near the centers of the piles.

(*c*) Initial weights and placing of whole pieces: In addition to the 24-inch samples it is desirable to select several representative whole pieces of stock and weigh them to an accuracy of one-tenth of 1 per cent on the platform scale. Mark the weights on the pieces and place them at various points near the tops, edges, bottoms, and centers of the piles.

(*d*) Determination of the direction, uniformity, and rate of air circulation: In order to insure correct placing of samples, whole pieces, and instruments it is necessary that the direction of the circulating air be known. To determine this light a few punk sticks, take the flash light, enter the kiln, close the door, and determine the direction, uniformity, and rate of motion of the circulating air in the spaces around the piles and through the piles by observing the smoke from the burning punk.

(*e*) Location and calibration of instruments: Having determined the direction in which the air passes through the piles, place the bulb of the recording thermometer in contact with a standardized glass thermometer close to the pile at the center of the side where the air enters the pile. If the circulation is up through the piles, place the thermometer bulbs close under the bottom center; if it is down through the lumber, place the bulbs close to the top center, and if the air moves through the pile laterally, place the bulbs close to the center of the side where the air enters the pile. It is also desirable to know the variation of temperature in different parts of the piles and kiln. To determine this variation, place several of the standardized thermometers in the tops, bottoms, edges, and centers of the piles and at different points in the kiln. In order to calibrate a recording thermometer, place the bulb in contact with a standardized glass thermometer in the kiln and adjust the stylus until it agrees with the glass thermometer. The temperature must not be fluctuating, as is often the case where it is controlled by a thermostat. It is best to use a steady steam pressure in the heating pipes while calibrating instruments. Never attempt to calibrate a recording thermometer out of its place in the kiln.

To determine humidity, place the standardized glass wet and dry bulb hygrometer near the bulb of the recording thermometer, so as to indicate the humidity of the air entering the piles at the tops, bottoms, or edges, as the case may be.

2. *Current tests.*—(*a*) Determination of current temperatures: If any part of a pile is exposed to direct radiation from the heating pipes, place a thermometer near the side so exposed.

This will indicate whether or not any part is subject to higher temperature than that indicated by the recording instrument. If possible, allow no direct radiation on the lumber. The temperature of the air entering the piles must be known at all times, preferably by means of recording thermometers with extension bulbs which have been calibrated in place, as directed under 1 (*e*).

The temperatures in the tops, bottoms, edges, and centers of the piles and at different points in the kiln should be determined occasionally by using standardized thermometers located as directed under 1 (*e*).

(*b*) Determination of current humidities: Never attempt to determine the relative humidity of the air where the bulbs of the hygrometer are exposed to direct radiation. Where direct radiation may take place, it is necessary to shield the hygrometer from the heating pipes before readings are taken. The relative humidity of the air entering the piles must be indicated at all times by means of standardized glass wet and dry bulb hygrometers placed as directed under 1 (*e*). Before reading the hygrometer fan the bulbs briskly for about a minute. An air circulation of at least 15 feet per second past the wet bulb is necessary for an accurate humidity reading. The wick should be of thin silk or linen and it must be free from oil or dirt at all times. It should come into close contact with as much of the bulb as possible. Knowing the correct wet and dry bulb hygrometer readings, the relative humidity may be determined from the humidity diagram, figure 26.

Relative humidity is shown on the horizontal scale and Fahrenheit temperature on the vertical scale. The curves running from the top left to the bottom right part of the chart are for various differences in the wet and dry bulb readings. The curves are numbered near the center of the chart above the heading "$(t—t^1)$ degrees Fahrenheit." To get the relative humidity, follow the curve which is numbered to correspond to the difference of the wet and dry bulb readings till it intersects the horizontal line numbered to correspond to the dry bulb reading. Directly below this intersection in a vertical line will be found the relative humidity on the bottom scale. Example: Dry bulb reading, 120; wet bulb reading, 113; difference, 7. Curve 7 intersects horizontal line 120 at vertical line 79. Relative humidity is 79 per cent.

When the humidity is desired in a Tiemann kiln, use the set of curves running from the top right to the bottom left part of the chart. Locate the lower of the two thermometer readings on the scale at the right of the chart. This is the reading of the thermometer in the baffle box. Follow along parallel to the nearest curve till the horizontal line is crossed whose number is the higher thermometer reading. Vertically below this point of intersection on the lower scale will be found the relative humidity. Example: Baffle thermometer reading, 112°; flue thermometer reading, 120°. Start at 112 on right-hand scale, follow parallel to curve 28 till horizontal line 120 is crossed. This point falls on vertical line 80. Relative humidity is 80 per cent.

(*c*) Determination of circulation: During each drying operation the circulation of the air should be tested several times, as under 1 (*d*). As the lumber becomes drier, it has less cooling effect on the air, and this may change the circulation in the kiln. If this occurs, corresponding changes in the location of instruments should be made.

(*d*) Weighing of samples and determination of current moisture condition: The 24-inch samples, placed as directed under 1 (*b*), should be weighed daily to an accuracy of one-tenth of 1 per cent on the platform scale. From test 1 (*a*) the initial moisture contents of these samples are known. Their initial weights were determined by test 1 (*b*). Knowing their initial moisture contents and weights, their oven-dry weights may be computed from the formula:

$$\text{Oven-dry weight of sample} = \frac{\text{initial weight}}{100 + \text{initial moisture content}} \times 100$$

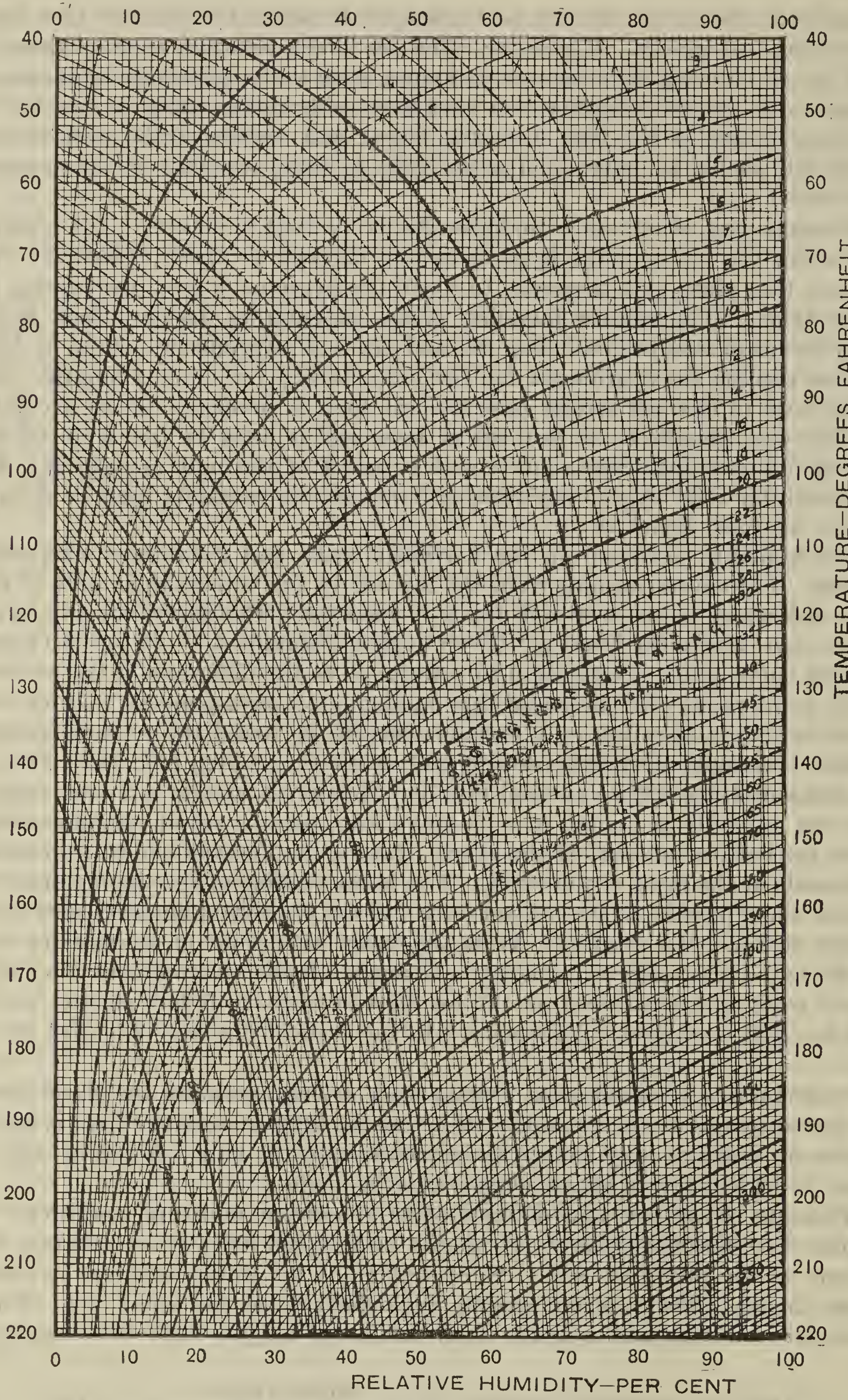
0 10 20 30 40 50 60 70 80 90 100
40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220
TEMPERATURE—DEGREES FAHRENHEIT
RELATIVE HUMIDITY—PER CENT

Fig. 26.

Having the calculated oven-dry weights and daily weights of the samples, their current moisture contents may be computed from the formula:

$$\text{Current moisture content of sample} = \frac{\text{current weight—oven-dry weight}}{\text{oven-dry weight}} \times 100$$

Therefore, since the samples were cut from representative stock, the drying rate of the material is known currently.

3. *Final tests.*—(*a*) Average kiln-dry moisture condition of samples: When the current moisture contents of the samples indicate that the material is dried to the required point, three 1-inch sections are cut from the center of each sample. One section from each sample is used to determine the average kiln-dry moisture content of each sample by the method of test 1 (*a*). This test must be made immediately after sawing.

(*b*) Distribution of moisture in kiln-dry samples: A thin shell (about one-fourth inch) is split from the four outer surfaces of the second 1-inch section cut from each sample. The outsides and centers are tested for moisture content separately and immediately after sawing by the method of 1 (*a*). The results of this test show the distribution of moisture in cross section of the samples. The difference between the moisture contents of the outer shells and the centers shows whether or not the distribution is sufficiently uniform across the sections.

(*c*) Determination of casehardening in kiln-dry samples: The first indication of case-hardening is surface checking. The next sign of case-hardening is honeycombing or interior checking along the medullary rays. This defect can not always be detected by a superficial inspection. It is necessary to cut the stock to discover it. Occasionally it is evidenced by a bulging of the surface over the honeycombed part. Often neither of these defects is present. In this case the third 1-inch section from each sample is resawed two or three times from one end down to within about half an inch of the other end (see fig. 23). If the material is case-hardened and dry, it will pinch the saw; if it is not dry at the time of sawing, the cupping of the outer prongs will increase upon further drying. If the kiln-dried samples show case-hardening, the material should be steamed until the resawed sections do not pinch the saw in this test.

(*d*) Average kiln-dry moisture condition of the whole pieces: When the kiln is unloaded, the whole pieces from different parts of the piles and kiln are weighed and then cut as follows: Remove about 2 feet from one end and then cut off three 1-inch sections. The average kiln-dry moisture contents of the whole pieces are determined from one section as in test 3 (*a*). The other sections are used as stated in 3 (*f*) and 3 (*g*).

(*e*) Calculation of initial moisture condition of whole pieces: From the kiln-dry weights and kiln-dry moisture contents of the whole pieces, their oven-dry weights may be computed from the formula:

$$\text{Oven-dry weight of whole pieces} = \frac{\text{kiln-dry weight}}{100 + \text{kiln-dry moisture content}} \times 100$$

Knowing the initial weights and oven-dry weights of the whole pieces, their initial moisture contents are computed from the formula:

$$\text{Initial moisture content of whole pieces} = \frac{\text{initial weight—oven-dry weight}}{\text{oven-dry weight}} \times 100$$

Therefore the initial and kiln-dry moisture conditions of the samples, whole pieces, and the average stock are known.

(*f*) Distribution of moisture in kiln-dry whole pieces: This test is a duplicate of test 3 (*b*).

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(*g*) Determination of case-hardening in kiln-dry whole pieces: This test is a duplicate of test 3 (*c*).

(*h*) To determine the effect of drying on the strength of the stock: It is practically impossible to determine the effect of the process of drying on the properties of the stock by inspection unless some visible defect has developed. This is not usual, and as the inspector can not always resort to mechanical tests he should be able to show from his operation records that conditions in the kiln have been kept within the specifications recommended as safe for kiln-drying airplane stock.

Detailed instructions for the kiln drying of various airplane woods have been prepared and issued in the form of a specification. This specification, which follows, is based upon a great many experimental kiln runs and strength tests upon matched specimens. Part of the matched specimens were tested while green, part were tested after air drying under shelter, and part were kiln dried to the same degree as the air-dried specimens and then tested. In this way the effect of kiln drying as compared to air drying was investigated and the conditions of kiln drying were determined for most rapid drying without decreasing the strength below that obtained in air drying to the same degree.

SPECIFICATION FOR KILN DRYING FOR AIRCRAFT STOCK.

GENERAL.

1. This specification covers general requirements for kiln drying wood for airplane stock.
2. The kiln-drying operations shall be so conducted that the wood will not lose any strength, toughness, or other physical property as compared to wood air dried to the same degree of dryness.

MATERIAL.

3. Only one species and approximately one thickness shall constitute a kiln charge. A difference of not to exceed one-half inch in the thickness of single pieces will be allowed.

PILING.

4. The boards shall be piled so that the horizontal width of the spaces between them will be at least 1 inch for each inch of board thickness, but in no case shall the horizontal width of such spaces exceed 3 inches. The boards must be held flat and straight while drying.
5. For stock up to four-quarters (1 inch) in thickness the crossers shall be at least 1 inch thick and not over $1\frac{1}{2}$ inches wide.
6. For stock from four to twelve quarters (1 to 3 inches) in thickness the crossers shall be at least $1\frac{1}{2}$ inches thick and not over $1\frac{1}{2}$ inches wide.
7. For stock over twelve quarters (3 inches) in thickness the thickness of the crossers shall be increased in the above proportion but must not exceed 2 inches in any case.
8. The crossers shall be placed directly over one another and not over 3 feet apart in the courses.
9. The lumber must be so disposed in the kiln as to permit of easy access on both sides of the pile and the taking of temperature and humidity readings whenever required by the inspector.

INSTRUMENTS.

10. At least one recording thermometer or recording hygrometer of approved make shall be used in each dry kiln compartment.
11. Recording thermometers and hygrometers shall be checked at least once every kiln run with a standard thermometer or a glass thermometer calibrated to an accuracy of 1° F. This comparison shall be made with the thermometers placed so as to record the maximum temperature of any portion of the pile.

12. *Thermometers.*—Thermometer bulbs must be shielded from direct radiation from steam pipes, wet lumber, cold walls or surfaces, and must receive a free circulation of air.

13. The inspector may, at his discretion, place other thermometers at any point in the pile.

14. *Hygrometer.*—Humidity readings shall be made at least three times daily or more often as the inspector may desire, according to standard methods approved by the inspector, at the same points where the bulbs for the recording thermometers and hygrometers are placed.

15. The following shall constitute a standard method: Use a glass or recording wet and dry bulb hygrometer with distilled water and with the wick changed at least once a week; produce a circulation of air past the wet bulb of at least 15 feet per second before reading.

16. Hygrometer bulbs must be shielded from direct radiation of steam pipes, wet lumber, and cold walls or surfaces, and must receive a free circulation of air.

STEAMING.

17. *At the beginning of the drying operations.*—Green wood is to be steamed at a temperature not to exceed 15° F. higher than the initial drying temperature specified in tables 5 and 6 for six hours for each inch of thickness. Humidity during steaming period must be 100 per cent, or not below 90 per cent, in every portion of the pile.

18. Previously air-dried wood is to be steamed at a temperature not to exceed 30° F. higher than the initial drying temperature specified in tables 5 and 6 for eight hours for each inch of thickness. Humidity during steaming period must be 100 per cent, or not below 90 per cent, in every portion of the pile.

19. *Near the end of the drying.*—If on official test the stock shows serious casehardening it shall be steamed at a temperature not to exceed 20° F. higher than the final drying temperature specified in tables 5 and 6 for not more than three hours. After steaming it shall be redried.

TEMPERATURE AND HUMIDITY.

20. Operating conditions are specified in tables 5 and 6, but lower temperatures and higher humidity conditions are permissible.

21. The progression from one specified stage to the next must proceed without abrupt changes.

22. *Green wood (above 25 per cent moisture) over 3 inches thick.*—Reduce the temperature values given in tables 5 and 6 by 5° F. for each inch increase in thickness.

23. *Air-seasoned wood (below 25 per cent moisture) over 3 inches thick.*—Reduce the temperature values given in tables 5 and 6 by 5° F. for each inch increase in thickness.

TABLE 5.

Stage of drying.	Drying conditions.	
	Maximum temperature.	Minimum relative humidity.
	°*F.*	*Per cent.*
At the beginning	120	80
After fiber saturation is passed (25 per cent)	125	70
At 20 per cent moisture	128	60
At 15 per cent moisture	138	44
At 12 per cent moisture	142	38
At 8 per cent moisture	145	33
Final	145	33

24. Table 5 applies to the following woods:

Ash, white, blue, and Biltmore.
Birch, yellow.
Cedar, incense.
Cedar, northern white.
Cedar, western red.
Cedar, Port Orford.
Cypress.
Pine, sugar.
Pine, white (Idaho or eastern).
Spruce, eastern (red or white).
Spruce, Sitka.
Fir, Douglas.

TABLE 6.

Stage of drying.	Drying conditions.	
	Maximum temperature.	Minimum relative humidity.
	°F.	*Per cent.*
At the beginning	105	85
After fiber saturation is passed (25 per cent)	110	73
At 20 per cent moisture	117	62
At 15 per cent moisture	129	46
At 12 per cent moisture	135	42
At 8 per cent moisture	135	40
Final	135	40

25. Table 6 applies to the following woods:

Cherry.
Mahogany.
Oak, white and red.
Walnut, black.
Maple.

TESTS DURING DRYING.

26. Samples shall be inserted in the pile in such manner that they will be subjected to the same drying conditions as that portion of the pile where inserted. They shall be so placed that they can be removed for periodical weighing in order to ascertain the average moisture content of the pile at any time.

27. Three samples shall be used for each 10,000 board feet or less of material in the pile. Each sample is to be 2 feet long and shall not be cut nearer than 2 feet to the end of one of the pieces to be dried.

28. The original moisture content of the samples shall be determined from sections 1 inch thick cut from both ends of the sample at the time it is sawed from the stick. This determination shall be made as provided in the specifications. (See Appendix, p. 147.)

29. Before placing them in the pile, the ends of the samples must be given a thorough coating of asphaltum varnish to prevent end drying.

30. The samples shall be weighed to an accuracy of one-tenth of 1 per cent immediately after cutting the moisture sections and before placing in the kiln. They shall be weighed at least daily when the time of drying is 10 days or less, and at least every other day when the time of drying is more than 10 days.

31. The samples shall be placed in the pile and distributed so that they will be exposed to the average, most rapid, and slowest drying, except that they shall not be placed on the top or bottom layers. The samples placed in the portion of the pile where drying is most rapid shall control the regulation of the temperature and humidity.

32. After obtaining the dry weight of the samples, the average moisture condition of the pile during drying shall be determined after each weighing.

33. The following example will illustrate the method employed:

Original weight of sample = 7.35 pounds.
Original moisture per cent (average of the two 1-inch sections) = 47.
Calculated dry weight of sample = 7.35 divided by 1.47 = 5.00 pounds.
Current weight = 6.23 pounds.
Moisture in samples = 6.23 − 5.00 = 1.23 pounds.
Current moisture per cent = (1.23 divided by 5.00) × 100 = 24.6.

34. Continuous and permanent records must be kept of the temperature and humidity observations and the percentage of moisture in the lumber in the kiln.

TESTS AFTER DRYING.

35. Standard moisture content and case-hardening tests shall be made before the lumber is removed from the kiln. Material for these tests shall be taken from four boards for each 5,000 board feet or less of material in the pile. Pieces selected must fairly represent the dried stock and shall be taken from different parts of the pile. At his discretion, the inspector may select other pieces for tests. Sections for these tests shall not be cut nearer than 2 feet to the ends of the pieces.

36. Three adjacent sections 1 inch thick shall be cut from the centers of each test piece of stock. Each section must be weighed within five minutes to prevent moisture evaporation.

37. The first section (A, fig. 27) shall be dried whole and the average moisture content obtained as provided in specifications.

38. The second section (B, fig. 27, moisture distribution) shall be cut into an outer shell ¼ inch wide and an inner core ½ inch wide. The moisture content of the outer shell and inner core shall be determined.

39. The third section (C, fig. 27) shall be sawed parallel to the wide faces of the original board into tongues or prongs, leaving about ½ inch of solid wood at one end of the section. For material less than 2 inches thick two saw cuts shall be made and for material more than 2 inches thick five saw cuts shall be made. In sections having six prongs the second prong from each side shall be broken out, leaving two outer and two central prongs. The center prong shall be removed from sections having only three prongs.

40. The third section shall then be allowed to dry for 24 hours in the drying room and any curving of the prongs noted.

41. If the prongs remain straight, perfect conditions of stress and moisture content are indicated.

42. If the outer prongs bend in, conditions of casehardening are indicated.

43. Only very slight casehardening is permissible.

FINAL MOISTURE CONDITIONS.

44. An average dryness of approximately 8 per cent, unless otherwise specified,* shall be required. A moisture content of from 5 to 11 per cent is permissible in individual sticks.

45. The variation in moisture content between the interior and exterior portions of the wood, as shown by the "moisture distribution section" provided for in paragraph 38, must not exceed 4 per cent.

SEASONING.

46. Before manufacture the wood shall be allowed to remain in a room, with all parts under uniform shop conditions, at least two weeks for 3-inch material and other sizes in proportion.

*See Note 3.

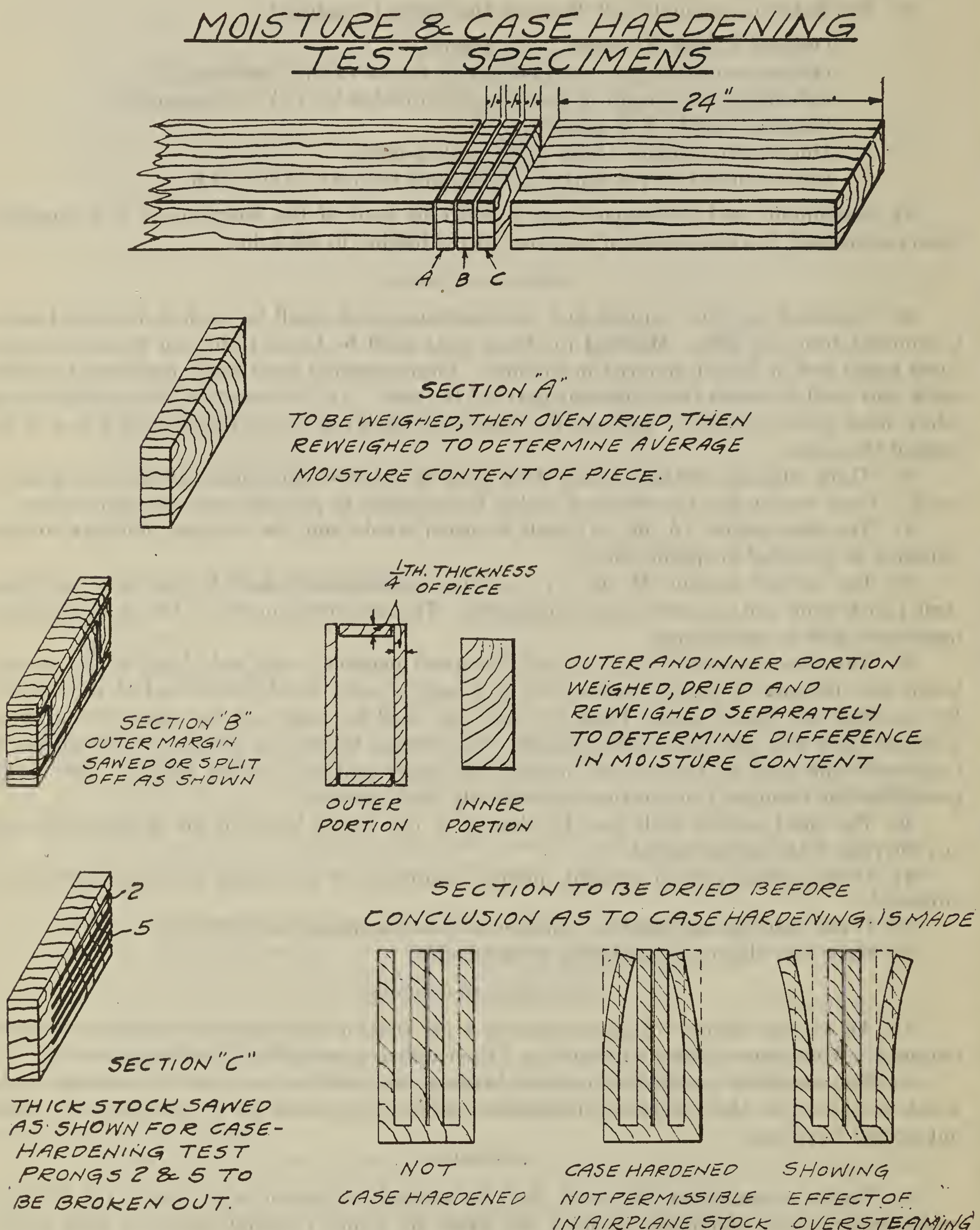

Fig. 27.—Moisture and casehardening test specimens.

STEAMING AND BENDING OF ASH FOR LONGERON CONSTRUCTION.

47. The ash shall be cut in the form of rough squares sufficiently large to allow for shrinkage and finish.

48. Where it is necessary to bend this material, it shall be steamed in the green condition (more than 18 per cent moisture), bent on forms, and then kiln dried, as provided in paragraph 23.

49. Steaming shall be conducted at a temperature not to exceed 212° F. for a period not longer than six hours and the bending shall be accomplished while the material is hot.

INSPECTION.

50. At all stages of the process the lumber shall be subjected to inspection by the inspection department.

51. The inspector shall mark all lumber with the official acceptance or rejection symbol.

52. The inspector shall have free access to every part of the kiln at all times and shall be afforded every reasonable opportunity to satisfy himself that this specification is being complied with.

NOTE 1. *Steaming.*—It has been found possible to dry spruce satisfactorily without steaming to relieve casehardening. A preliminary steaming is given at low temperature, and after the drying has been completed the material is held in the kiln for 24 hours, with a humidity of 75 per cent or 80 per cent, at room temperature.

NOTE 2. *Tests during drying.*—(Paragraph 31.) The most rapid drying sample should not be confused with the sample of lowest moisture content. If the original moisture content was practically the same for all samples, then at any stage of the run the low sample would be the most rapid drying. However, the original moisture content is not likely to be uniform for the whole charge, and with stock of varying moisture content the run should be controlled for the stock of high moisture content. Other things being equal, the sample with the highest moisture content will dry the most rapidly, so that in such a case the specification would still hold. It would therefore be desirable to place the high original sample where it will be the most rapid drying sample. Otherwise it would be necessary to take into account the high stock—possibly specify following the average of the samples on the entering air side of the pile provided the average is not more than 10 per cent below the high sample.

NOTE 3. *Final moisture content.*—For naval aircraft, it has been found desirable to have the moisture content on removal from the kiln about 12 per cent. The maximum individual variation allowed should not be over 3 per cent.

TREATMENT OF WOOD AFTER REMOVAL FROM THE KILN.

Lumber should be retained for at least two weeks after removal from the dry kiln in a shed or room where the conditions are approximately the same as in the shop where the material is to be worked up. The necessity for this will be understood upon consideration of the following facts: When lumber is drying in the kiln the outer surface is necessarily somewhat drier than the interior. In good methods of drying this difference is a minimum and in bad methods of drying it is excessive; but it exists to a certain extent in all methods of drying. When the lumber has been dried down to a point somewhat below the condition to which it will finally come when exposed to the normal shop working conditions, it will gradually reabsorb moisture on the outside. Thus, thoroughly kiln-dried lumber, if it has stood in an unheated room for some time, will be found to be drier on the inside than it is on the surface, though the difference is likely to be very small. Since differences in moisture content are indicative of internal stresses existing in the wood, it is evidently desirable to have the moisture distribution as uniform as possible before the lumber is made up into finished products; otherwise the adjustment of stresses, when the lumber has been cut up, will cause warping, checking, or other troubles.

Just how long lumber should remain in the shop air after being kiln-dried will depend, of course, upon a great many circumstances. Generally speaking, the longer it remains the better it will be, provided the moisture conditions of the room in which it is stored are suitable. The same kind of a test as has been explained for casehardening occurring in the dry kiln will apply as a test of the lumber after remaining in storage, to see whether the internal stresses have been neutralized.

Even if casehardening has been removed in the dry kiln by resteaming at the end of the drying period, there may still exist within the lumber slight differences in moisture content which will gradually adjust themselves under proper storage conditions, so that material which has been steamed before removal from the kiln is also benefited by being allowed to stand in the room before it is manufactured. Recent experiments have shown that the length of time required for kiln-dried stock to reach a state of equilibrium under shop conditions after removal from the kiln may be reduced very materially by allowing it to remain in the kiln for about 24 hours, after the drying has been completed, at a humidity of 75 per cent or 80 per cent and shop temperature.

Ideal conditions for the storage and manufacturing of lumber require regulation of the humidity, which should be kept slightly below that of the average conditions to which the lumber is to be subjected after it is put into service. The nearer these conditions are actually met in practice the better are the results to be expected, particularly where requirements are so exacting as in the construction of airplanes.

CHANGES OF MOISTURE IN WOOD WITH HUMIDITY OF AIR.

Wood is a hygroscopic material; that is, it has the property of absorbing moisture from the air or surrounding medium. It has already been explained that there are two different kinds of moisture found in wood, namely, free water, which occupies the openings in the cell structure of the wood, and hygroscopic water, which is actually taken into the cell walls and which upon being removed or added to wood causes shrinkage or swelling.

There is a definite moisture content to which wood will eventually come if it is held in an atmosphere which is at a constant humidity and temperature. The moisture content of wood will vary with the average atmospheric conditions, also with the size of the material. Thus, ordinary lumber which is stored in the open during the summer months for sufficient time will eventually attain a moisture content of from 8 to 15 per cent, and wood stored indoors in a heated building will in time fall to about 5 or 6 per cent because of the lower relative humidity. If the relative humidity is constant, an increase in temperature decreases the moisture-holding power of the wood. However, the moisture content is not appreciably affected by temperature within a range of 25° to 30° F.

Figure 28 shows the relation between the moisture content of wood and the humidity conditions of the atmosphere. The data for the curve were obtained by keeping the wood at a constant humidity and temperature until no further change in moisture occurred. This curve can be used as an aid in controlling the moisture conditions of wood, the approximate atmospheric condition being known, and in determining the proper humidities for storing lumber in order to secure a certain moisture content and give uniform material for use in fine wood jointing, propellers, etc. It is of importance to have wood to be used for propellers of uniform moisture content. The curve may be used also to prepare wood for use in a given locality, such as the border States, where the humidity is usually very low. Propellers for use under such conditions should be made up at a low moisture content, in order that there may be less tendency for moisture changes to take place when they are put in service. It must be remembered that this curve must not be used for dry-kiln work because of the fact that the dry-kiln temperatures used are higher than those at which the data were collected Furthermore, the curve represents the ultimate moisture content at a given temperature and humidity, and in the case of large pieces of wood this moisture content would not be reached for a long period of time. Kiln drying tends to reduce the hygroscopic properties of wood, hence curves for kiln-dried wood are lower than the one given. For example, wood that had been dried to 2 per cent moisture, or less, if subjected to humidities between 30 and 70 per cent, would probably show a corresponding moisture content about 1½ to 2½ per cent lower than in the curve in figure 28.

VENEER AND PLYWOOD.

VENEER.

Veneer may be loosely defined as thin wood. It usually varies in thickness from one-hundredth inch to one-eighth inch, though it is commercially possible to cut it thinner, and thicker sizes are to be obtained. However, in general, veneer used in aircraft falls within the limits stated.

There are three common methods of manufacturing veneer, as follows: (1) The rotary process, (2) the slicing process, (3) the sawing process.

By far the greater portion of all veneer manufactured is made by the rotary process. Veneer made by this process is all slash cut, and the length along the grain is limited by the length of the veneer lathe. Rotary veneer longer than 100 inches is more or less uncommon.

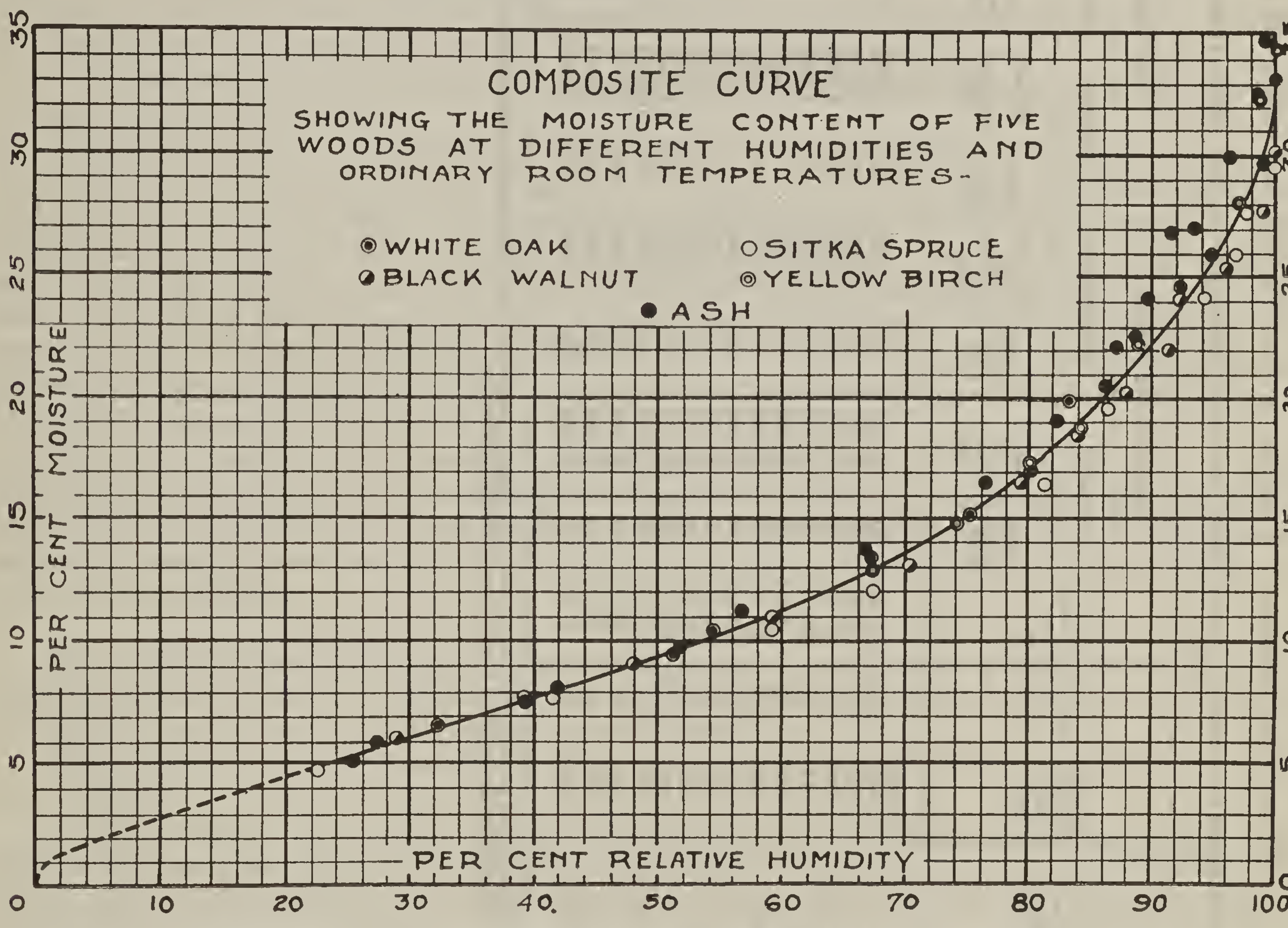

Fig. 28.—Composite curve of moisture content of fine woods at different humidities and ordinary room temperature.

Sliced veneer is usually manufactured only from the finer woods. On account of the fact that it is possible to produce quartered veneer on slicing machines, and the waste on account of saw kerf is absent, this method of manufacture is preferred where pattern is important and the value of the wood is great. The length parallel to the grain of sliced veneer is limited by the length of the knife.

Sawed veneer can be produced in almost any reasonable length and from any kind of stock. The material produced may be either quartered or slash. In general, sawed veneer will not be specified for aircraft uses, to the exclusion of rotary stock, except where it is necessary to have extra long lengths or quartered stock or for some other reason it is impossible to secure the stock by rotary cutting. It may happen, for instance, that the stock from which the veneer is to be cut can not be handled to advantage in a rotary lathe on account of its shape.

TABLE 7.—*Comparative strengths of 5 species of sawed, sliced, and rotary-cut plywood.*

Each panel composed of 3 plies of $\frac{1}{16}$-inch veneer; grain of successive plies at right angles; casein glue used.

	Method of manufacture.	Average panel thickness.	Specific gravity.†	Per cent moisture.	Column-bending modulus.				Tensile strength.				Splitting resistance.		
					Parallel.*		Perpendicular.*		Parallel.*		Perpendicular.*				
					Number of tests.	Pounds per square inch.	Number of tests.	Pounds per square inch.	Number of tests.	Pounds per square inch.	Number of tests.	Pounds per square inch.	Number of tests.	Total work in splitting, inch-pounds.	Splitting modulus, inch-pounds per inch.
		Inches.													
Ash, commercial white	Sawed	0.206	0.55	11.4	10	8,220	10	2,160	10	6,810	10	4,310	20	910	4,400
Do	Sliced	.183	.56	10.9	10	9,670	10	1,940	10	7,040	10	4,770	20	690	3,790
Do	Rotary cut	.193	.52	12.0	10	7,180	10	1,810	10	4,290	10	3,180	20	650	3,350
Birch	Sawed	.194	.65	10.1	8	10,520	8	2,660	8	8,600	8	6,590	16	1,620	8,360
Do	Sliced	.169	.65	9.4	9	9,670	9	1,760	9	9,230	9	5,760	18	1,460	8,660
Do	Rotary cut	.182	.61	10.3	10	11,330	10	2,340	10	11,350	10	5,970	20	1,360	7,460
Mahogany, African	Sawed	.212	.53	10.0	10	7,930	10	2,000	10	7,220	10	4,200	20	1,770	8,380
Do	Sliced	.170	.52	11.0	6	8,360	6	2,110	6	6,690	6	4,270	72	1,180	6,920
Maple, sugar	Sawed	.196	.67	11.2	9	13,670	9	2,750	9	11,810	9	6,810	18	1,230	6,250
Do	Sliced	.176	.67	10.2	10	13,400	10	2,480	10	11,340	10	6,770	20	1,110	6,290
Do	Rotary cut	.134	.67	10.8	10	12,650	10	2,300	10	10,140	10	5,750	20	1,250	6,450
Poplar, yellow	Sawed	.194	.51	8.7	10	8,630	10	1,950	10	9,610	10	4,780	20	1,150	5,960
Do	Sliced	.172	.50	8.5	10	9,060	10	1,790	10	8,140	10	4,720	20	890	5,180
Do	Rotary cut	.179	.50	8.8	10	7,710	10	1,580	10	8,540	10	4,180	20	805	4,500

* Parallel and perpendicular refer to direction of grain of faces relative to direction of application of force.
† Specific gravity based on oven-dry weight and volume at test.

A special series of tests was made to determine the effect of the method of cutting veneer on the strength of plywood panels made from it. Detailed results are presented in table 7, and the general conclusions drawn follow:

(*a*) The effect of the method of cutting veneer on the strength of plywood depends on the species cut, although in general, the effect, as shown by the bending and tension tests, is not great.

(*b*) Of the three methods of cutting, the sawed and sliced material, for the species tested, gave the more similar results. The commercial white ash, sugar maple, and yellow poplar pannels cut by these methods were slightly superior in bending and tensile strength to the rotary-cut panels.

(*c*) For birch the panels of rotary-cut veneer were slightly superior in bending and tensile strength to panels of either sawed or sliced veneer.

(*d*) For the species tested, with the possible exception of the African mahogany, panels of sawed veneer twist less than panels of either sliced or rotary-cut veneer.

(*e*) With the exception of birch the results show little difference in the twisting of panels of sliced or rotary-cut veneer.

For the convenient calculation of the weight of veneer and plywood, table 8 has been prepared. This table presents the weights, per square foot, of veneer of various thicknesses and species, at the average air-dry moisture condition shown in the second column. The weight of blood albumen glue per square foot and the weight of a typical casein glue (Certus) per square foot are also given, so that it is possible to calculate the average weight of any plywood made up of the species listed and using blood or casein glue. This is done simply by adding together the weights of the individual plies and the weight of the glue, which is obtained by multiplying the weight of the glue per square foot by the number of glue lines in the plywood. This number is always one less than the number of plies.

While it is usually not necessary to know the tensile strength of single-ply veneer as such, this figure is very convenient in computing the probable strength in tension of plywood made up in various manners. The last column of table 9 presents computed tensile strengths of single-ply veneer. Reference to the other data in this table will be found in the text under the discussion of plywood.

PLYWOOD.

In general plywood consists of a number of layers of wood veneer glued together by some suitable glue or adhesive. Occasionally the term is applied to material in which one or more of the layers are composed of some other material than wood.

The weight of plywood has already been discussed in connection with the weight of veneer (see table 8).

Until recently little information was available on the mechanical properties of plywood. Within the last year and a half, however, about 50,000 tests have been made and tabulated. Since the subject is rather new, a full discussion is presented, followed by tables of strength properties.

PROPERTIES OF WOOD PARALLEL AND PERPENDICULAR TO THE GRAIN.

Wood, as is well known, is a nonhomegenous material with widely different properties in the various directions relative to grain. This difference must be recognized in all wood construction, and the size and form of parts and placement of wood should be such as to utilize to the best advantage the difference in properties along and across the grain. It is the strength of the fibers in the direction of the grain that gives wood its relatively high modulus of rupture, and tensile and compressive strength parallel to the grain. Were it a homogenous material, such as cast iron, having the same strength properties in all directions that it has parallel to the grain, it would be unexcelled for all structural parts where strength with small weight is desired. As it is the tensile strength of wood may be 20 times as high parallel to the grain as perpendicular to the grain and its modulus of elasticity from 15 to 20 times as high.

TABLE 8.—*Weights of veneer.*

[In ounces per square foot of one-ply, oven-dry; veneer thicknesses in inches.]

Species.	Specific gravity oven-dry based on volume air-dry.	Air-dry moisture content, per cent.	$\frac{1}{100}$	$\frac{1}{80}$	$\frac{1}{64}$	$\frac{1}{60}$	$\frac{1}{55}$	$\frac{1}{48}$	$\frac{1}{40}$	$\frac{1}{32}$	$\frac{1}{28}$	$\frac{1}{24}$	$\frac{1}{20}$	$\frac{1}{16}$	$\frac{1}{12}$	$\frac{1}{10}$	$\frac{1}{8}$	$\frac{1}{6}$	$\frac{3}{16}$	$\frac{1}{4}$
Ash, black	0.50	10.4	0.42	0.52	0.65	0.69	0.76	0.87	1.04	1.30	1.49	1.74	2.08	2.60	3.47	4.16	5.20	6.94	7.81	10.41
Ash, commercial white	.58	8.9	.48	.60	.75	.80	.88	1.00	1.21	1.51	1.72	2.01	2.41	3.02	4.02	4.82	6.04	8.05	9.05	12.06
Basswood	.38	8.4	.32	.40	.49	.53	.58	.66	.79	.99	1.13	1.32	1.58	1.98	2.64	3.16	3.96	5.28	5.94	7.92
Beech	.63	11.2	.52	.66	.82	.87	.95	1.09	1.31	1.64	1.87	2.19	2.62	3.28	4.37	5.24	6.56	8.74	9.84	13.12
Birch, yellow	.63	9.6	.52	.66	.82	.87	.95	1.09	1.31	1.64	1.87	2.19	2.62	3.28	4.37	5.24	6.56	8.74	9.84	13.12
Butternut	.39	7.6	.32	.41	.51	.54	.59	.68	.81	1.02	1.16	1.35	1.62	2.03	2.71	3.25	4.06	5.42	6.09	8.12
Cedar, Spanish	.37	7.3	.31	.38	.48	.51	.56	.64	.77	.96	1.10	1.28	1.54	1.92	2.57	3.08	3.85	5.13	5.78	7.70
Cherry, black	.51	9.2	.42	.53	.66	.71	.77	.88	1.06	1.33	1.52	1.77	2.12	2.65	3.54	4.25	5.31	7.08	7.96	10.62
Chestnut	.44	8.6	.37	.46	.57	.61	.67	.76	.92	1.14	1.31	1.53	1.83	2.29	3.05	3.66	4.58	6.10	6.87	9.16
Cottonwood (common)	.43	4.7	.36	.45	.56	.60	.65	.75	.90	1.12	1.28	1.49	1.79	2.24	2.98	3.58	4.47	5.97	6.71	8.96
Cypress, bald	.44	9.0	.37	.46	.57	.61	.67	.76	.92	1.14	1.31	1.53	1.83	2.29	3.05	3.66	4.58	6.10	6.87	9.16
Douglas fir (coast type)	.51	6.2	.42	.53	.66	.71	.77	.88	1.06	1.33	1.52	1.77	2.12	2.65	3.54	4.25	5.31	7.08	7.96	10.62
Douglas fir (mountain type)	.44	9.4	.37	.46	.57	.61	.67	.76	.92	1.14	1.31	1.53	1.83	2.29	3.05	3.66	4.58	6.10	6.87	9.16
Elm, white	.51	8.8	.42	.53	.66	.71	.77	.88	1.06	1.33	1.52	1.77	2.12	2.65	3.54	4.25	5.31	7.08	7.96	10.62
Gum, black	.52	7.2	.43	.54	.68	.72	.79	.90	1.08	1.35	1.55	1.80	2.17	2.71	3.61	4.35	5.42	7.32	8.12	10.82
Gum, cotton	.52	6.1	.43	.54	.68	.72	.79	.90	1.08	1.35	1.55	1.80	2.17	2.71	3.61	4.35	5.42	7.32	8.12	10.82
Gum, red	.49	11.3	.41	.51	.64	.68	.74	.85	1.02	1.28	1.46	1.70	2.04	2.55	3.40	4.08	5.10	6.80	7.66	10.20
Hackberry	.54	9.2	.45	.56	.70	.75	.82	.94	1.12	1.40	1.61	1.87	2.25	2.81	3.75	4.49	5.62	7.49	8.43	11.24
Hemlock, western	.42	8.6	.35	.44	.55	.58	.64	.73	.87	1.09	1.25	1.46	1.75	2.18	2.91	3.50	4.37	5.83	6.56	8.74
Magnolia (evergreen)	.51	8.8	.42	.53	.66	.71	.77	.88	1.06	1.33	1.52	1.77	2.12	2.65	3.54	4.25	5.31	7.08	7.96	10.62
Mahogany (Central American)	.49	7.9	.41	.51	.64	.68	.74	.85	1.02	1.28	1.46	1.70	2.04	2.55	3.40	4.08	5.10	6.80	7.66	10.20
Mahogany (African)	.46	8.0	.38	.48	.60	.64	.70	.80	.96	1.19	1.37	1.59	1.91	2.39	3.19	3.83	4.78	6.38	7.17	9.57
Maple (silver)	.48	8.2	.40	.50	.62	.67	.73	.83	1.00	1.25	1.43	1.67	2.00	2.50	3.33	4.00	5.00	6.66	7.50	7.00
Maple (sugar)	.62	10.5	.52	.65	.81	.86	.94	1.08	1.29	1.61	1.85	2.15	2.58	3.23	4.30	5.16	6.46	8.60	9.69	12.91
Oak, commercial red	.64	10.7	.53	.67	.83	.89	.97	1.11	1.33	1.66	1.90	2.22	2.66	3.33	4.44	5.32	6.66	8.88	9.99	13.3
Oak, commercial white	.68	11.0	.57	.71	.88	.94	1.03	1.18	1.41	1.77	2.02	2.36	2.83	3.54	4.72	5.66	7.08	9.43	10.61	14.1
Pine, long-leaf	.66	9.2	.55	.69	.86	.92	1.00	1.15	1.37	1.72	1.96	2.29	2.75	3.44	4.58	5.50	6.88	9.16	10.32	13.75
Pine, sugar	.37	11.4	.31	.38	.48	.51	.56	.64	.77	.96	1.10	1.28	1.54	1.92	2.57	3.08	3.85	5.13	5.78	7.70
Pine, short-leaf	.54	11.0	.45	.56	.70	.75	.82	.94	1.12	1.40	1.61	1.87	2.25	2.81	3.75	4.49	5.62	7.49	8.43	11.24
Pine, western yellow	.41	10.8	.34	.43	.53	.57	.62	.71	.85	1.07	1.22	1.42	1.71	2.13	2.84	3.41	4.27	5.69	6.40	8.54
Pine, white	.39	9.9	.32	.41	.51	.54	.59	.68	.81	1.02	1.16	1.35	1.62	2.03	2.71	3.25	4.06	5.42	6.09	8.12
Poplar, yellow	.41	6.1	.34	.43	.53	.57	.62	.71	.85	1.07	1.22	1.42	1.71	2.13	2.84	3.41	4.27	5.69	6.40	8.54
Spruce, Sitka	.38	8.9	.32	.40	.49	.53	.58	.66	.79	.99	1.13	1.32	1.58	1.98	2.64	3.16	3.96	5.28	5.94	7.92
Sycamore	.50	9.2	.42	.52	.65	.69	.76	.87	1.04	1.30	1.49	1.74	2.08	2.60	3.47	4.16	5.20	6.94	7.81	10.41
Tanguile (Philippine mahogany)	.54	11.8	.45	.56	.70	.75	.82	.94	1.12	1.40	1.61	1.87	2.25	2.81	3.75	4.49	5.62	7.49	8.43	11.24
Walnut, black	.57	4.8	.47	.59	.74	.79	.86	.99	1.19	1.48	1.70	1.98	2.37	2.97	3.96	4.75	5.94	7.92	8.91	11.87

Weight of glue per square foot: Blood albumen, about 0.3 ounce; Certus, about 0.4 ounce.

Sample.—To get the weight of a square foot of 5-ply wood consisting of 1 ply of $\frac{1}{12}$-inch basswood, 2 plies of $\frac{1}{16}$-inch basswood, and 2 plies of $\frac{1}{20}$-inch yellow birch for faces, at 12 per cent moisture, glued with Certus glue:

$$\text{Weight}=(1\times2.64+2\times1.98+2\times2.62)\ 1.12+4\times0.4=14.68 \text{ ounces.}$$

The weight of wood is quite variable, so that while the table given represents the average weights of material tested, large variations from these figures may be expected in individual pieces of veneer.

The example presented is slightly in error through neglecting the change in volume between the moisture content at 12 per cent and the moisture listed in the table.

In the case of shear the strength is reversed, the shearing strength perpendicular to the grain being much greater than the strength parallel to the grain. The low parallel-to-the-grain shearing strength makes the utilization of the tensile strength of wood along the grain difficult since failure will usually occur through shear at the fastening before the maximum tensile strength of the member is reached.

The large shrinkage of wood across the grain with changing moisture content may introduce distortion in a board that decreases its uses where a broad flat surface is desired. The shrinkage from the green to the oven-dry condition across the grain for a flat sawn board as determined by the average of 150 species is about 8 per cent, and for a quarter-sawed board about 4½ per cent, while the shrinkage parallel to the grain is practically negligible for most species.

PLYWOOD PANELS *v.* SOLID PANELS.

It is not always possible in a given use so to proportion a board or solid panel as to develop the necessary strength in every direction and at the same time to utilize the full strength of the wood in all directions of the grain. In such cases it is the purpose of plywood to meet this deficiency by crossbanding, which results in a redistribution of the material.

In building up plywood a step is made in obtaining equality of properites in two directions—parallel and perpendicular to the edge of a board. The greater the number of plies used for a given panel thickness, the more nearly homogeneous in properties is the finished panel. Thus, in an airplane engine mounting made of 15-ply veneer the mechanical properties of the panel in the direction parallel to the grain of the faces are almost the same as those in the direction at right angles to this. However, an increase in such properties as bending strength and modulus of elasticity at right angles to the grain of the faces is accompanied by a decrease of the values parallel to the grain of the faces with an increase of the number of plies. For a very large number of plies (of the same species and thickness) we may assume that the tensile strength in the two directions is the same and that it is equal to the average of the parallel-to-the-grain and perpendicular-to-the-grain values of an ordinary solid board or panel. This is not always exactly true, since the maximum stress of the plies with the grain at right angles to the force may not be reached at the same time as the maximum of the plies with the grain parallel to the force. Internal stresses due to change of moisture content may also tend to unbalance the strength ratio.

SYMMETRICAL CONSTRUCTION IN PLYWOOD.

On account of the great difference in shrinkage of wood in the direction parallel to the grain and perpendicular to it, a change in moisture content of plywood will inevitably either introduce or release internal stresses. Consider, for example, a three-ply construction and subject it to low-humidity conditions, so that the moisture content of the plywood is lowered. Because the grain of the core is at right angles to the grain of the faces, the core will tend to shrink a great deal more than the faces in the direction of the grain of the faces. This shrinkage subjects the faces to compression stresses and the core to tensile stresses. If the faces are of exactly the same thickness and of like density, the stresses are symmetrically distributed and no cupping should ensue.

Now consider that one face of a three-ply panel has been glued with the grain in the same direction as the core and that the moisture content of the panel is reduced. It is obvious that the internal stresses are now no longer symmetrically distributed, inasmuch as the compressive stress in one face has been removed. This face now shrinks a great deal more than the other face in the direction of the grain of the latter. The result is that cupping takes place. Figure 29a shows the effect of drying on a three-ply construction (unsymmetrical) in which the grain of two adjacent plies was parallel. The panel has curled up into a cylindrical surface with the

parallel plies on the inner side. By adding another ply at right angles to the core we see that symmetry could again be established and that while we would have a four-ply panel in reality it gives a three-ply construction with a core of double the face thickness and would be regarded as such.

The necessity for exercising care in sanding the faces of a panel is obvious, inasmuch as different thicknesses on the faces would introduce unequal forces with changing moisture content.

In order to obtain symmetry, it is also necessary that both faces or symmetrical plies be of the same species.

To summarize: A veneer panel must be symmetrically constructed in order to retain its form with changes of moisture. Symmetry is obtained by using an odd number of plies. The

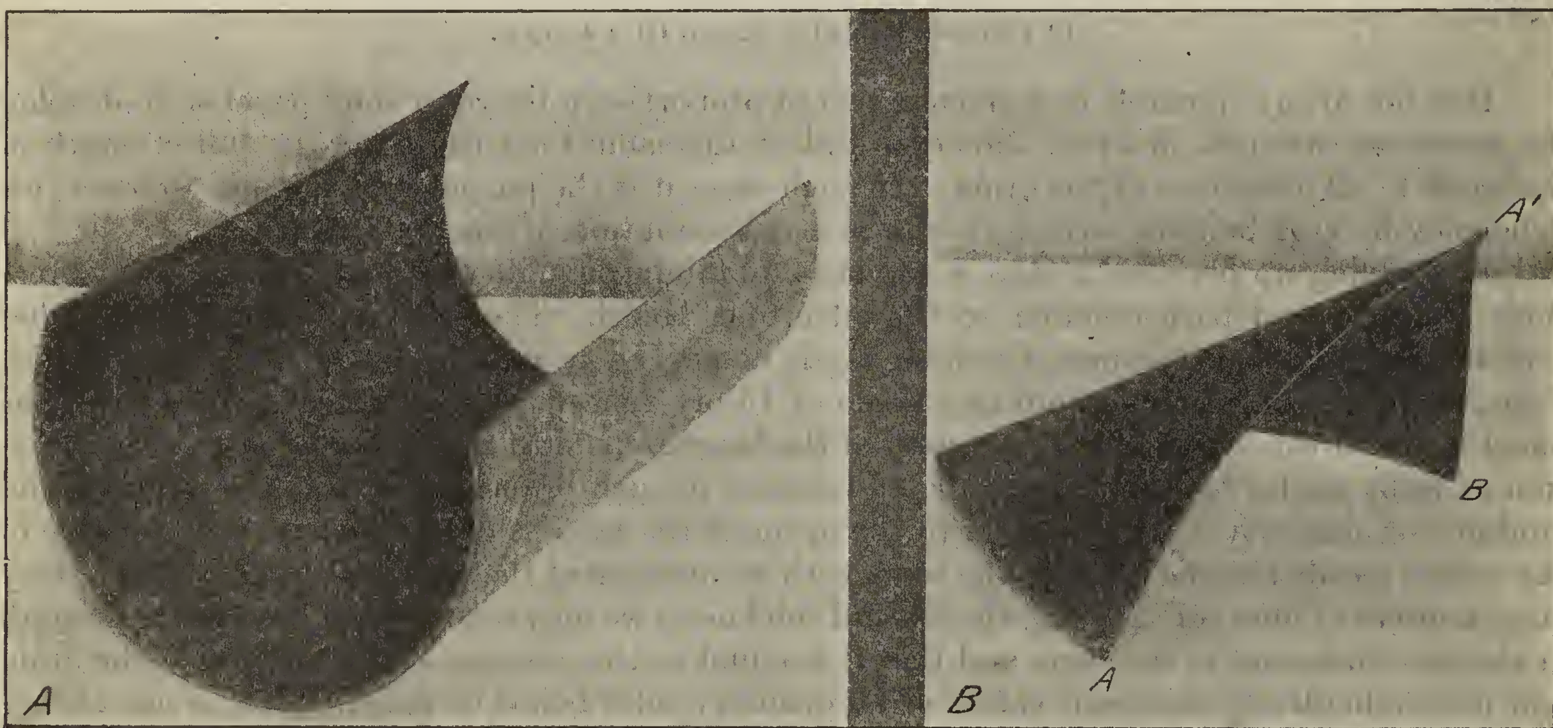

Fig. 29.—(a) Cupping resulting from unsymmetetrical construction in plywood. (b) Twisting resulting from plywood construction with grain of faces at 45 degrees with grain of core.

plies should be so arranged that for any ply of a particular thickness there is a parallel ply of the same thickness and of the same species on the opposite side of the core and equally removed from the core.

DIRECTION OF THE GRAIN OF ADJOINING PLIES.

In the discussion of symmetry of construction it was understood that the adjoining plies were always glued with the grain either parallel to or exactly at right angles to the core. In careless construction this may not always be the case. An extreme case of this kind is shown in figure 29b, in which the plies were glued so that the grain of each face of the panel was at 45 degrees with the grain of the core and so that the two faces were at 90 degrees with respect to each other. Whereas the unsymmetrical construction introduces cupping, a construction involving angles other than 0 and 90 degrees introduces twisting.

In building up a three-ply veneer panel the core should be glued with the grain at 90 degrees with the faces or as close to this as feasible.

EFFECT OF MOISTURE CONTENT.

The previous discussion has brought out the fact that a change in moisture content of a panel may introduce cupping and twisting in the panel if the panel is not carefully constructed. Hence it is highly desirable that the moisture content of the veneer before gluing be controlled

so as to make the moisture content of the finished panel when it leaves the clamps about the same as it will average when in use and that all plies be at the same moisture content before gluing. The limits of from 10 to 15 per cent moisture in the finished panel will usually give satisfactory results when the panel is in service in the open air.

SHRINKAGE OF PLYWOOD.

The shrinkage of plywood will vary with the species, the ratio of ply thickness, the number of plies, and the combination of species. The average shrinkage obtained in 54 tests on a variety of combinations of species and thicknesses in bringing three-ply wood from the soaked to the oven-dry condition was 0.45 per cent parallel to the face grain and 0.67 per cent perpendicular to the face grain, with the ranges of from 0.2 to 1 per cent and 0.3 to 1.2 per cent, respectively. Other combinations and thicknesses may extend these limits and change the average somewhat. The species included in the tests made were mahogany, birch, poplar, basswood, red gum, chestnut, cotton gum, elm, and pine.

EFFECT OF VARYING THE NUMBER OF PLIES.

The question frequently arises, Should three or more plies be used for a panel of a given thickness? The particular use to which the panel is to be put must answer this question. Commercial considerations will also enter. Veneer of most species less than $\frac{1}{48}$ inch thick can not be cut by the rotary process with uniform success, and while a number of species may be cut by slicing to $\frac{1}{64}$ inch and less, such material is limited in width.

In general it may be said that the greater the number of plies the flatter the plywood will remain when subjected to moisture variations.

If the same bending or tensile strength is desired in the two directions, parallel and perpendicular to the grain of the faces, the greater the number of plies the more nearly the desired result is obtained. This same result may be obtained by a proper selection of ratio of core to total plywood thickness in three-ply construction. It must be borne in mind, however, that a plywood with a large number of plies, while stronger at right angles to the grain of the faces, can not be as strong parallel to the grain of the faces as three-ply wood, and hence a three-ply panel is preferable where greater strength is desired in one direction than in the other. Table 11 gives strength values for three-ply, five-ply, and seven-ply yellow birch plywood.

Where great resistance to splitting is desired, such as in plywood that is fastened along the edges with screws and bolts and is subject to forces through the fastenings, a large number of plies affords a better fastening.

It is a common experience that a glued joint is weakened when two heavy laminations are glued with the grain crossed. The same weakness exists in plywood when thick plies are glued together. When plywood is subject to moisture changes, stresses in the glued joint due to shrinkage are greater for the thick plies than for the thin plies. Hence in plywood constructed with many thin plies the glued joints will not be as likely to fail as in plywood constructed of a smaller number of thick plies.

EFFECT OF VARYING THE RATIO OF CORE TO TOTAL THICKNESS.

At first thought it may seem that the proper selection of the ratio of core to total plywood thickness in three-ply construction may enable the designer to get the same strength in both directions as is possible with many-plied panels. While this is true in general, it is not true that the same ratio will serve for both tension and bending. In birch, for example, a ratio of core to total plywood thickness of 5 to 10 gives the same strength in tension in both directions,

but a ratio of about 7 to 10 gives the same strength in bending. For either ratio the plywood is not nearly as resistant to splitting as plywood of a greater number of plies totaling the same thickness.

SPECIES OF LOW DENSITY FOR CORES.

Where column strength and a flat panel are desired, full advantage of a strong species, such as birch, in the faces is best attained by using a thick core of a species, such as basswood or yellow poplar, rather than a thinner core of the same weight but of a species of geater density. A combination of strong faces and a thick light wood core has the advantage of greater separation of the faces than when using the thinner core of a heavier species, giving a marked increase in the internal resistance to forces that tend to bend the panel and a correspondingly great strength in bending with the same weight.

Consider, for example, that a certain panel contains a core of the same weight but of a specific gravity of one-half that of another core. This means that the core of lighter species is twice as thick as the core of high density and that the panel faces are spaced twice as far apart. In a long column, for instance, this is very desirable, for the maximum load a column can carry varies as the cube of the thickness. It is evident that a marked superiority in the load sustained might be expected in the low-density core panel over the high-density core panel of the same weight when the load is applied parallel to the grain of the faces.

The same line of reasoning applied to column strength may also be applied to resistance to cupping. A panel with a core of low density will cup less than a panel of the same weight with a core of high density. The load to produce failure in bending would likewise be greater for the former case.

PLYWOOD TEST DATA.

The column-bending modulus is obtained by loading a piece of plywood 5 inches by 12 inches as a column with the 12-inch length vertical. It is computed by the following formula:

$$S=\frac{P}{A}+\frac{6M}{bd^2},\ \text{where}$$

S = Column-bending modulus.
A = Area of cross section.
P = Load at maximum moment.
M = Maximum bending moment.
b = Width of test piece.
d = Thickness of test piece.

Like the modulus of rupture in the standard static bending test, the column-bending modulus is not a true stress existing in the fibers at the instant of failure. It is merely a measure of the magnitude of the external bending moment that a piece of plywood can withstand before it fails.

If a piece of plywood is subjected to forces that tend to bend it, as would be the case either in a long column or in a beam, the designer confronted with the problem of determining its proper thickness may use the column-bending modulus in exactly the same way that the modulus of rupture is used. It will be noted, of course, that the column-bending modulus must be used which applies to the particular plywood construction desired. The total plywood thickness is to be used in all equations involving the column-bending modulus.

The use of the tensile strength data is obvious. The strength values given are based on the total plywood thickness. (Table 9.)

TABLE No. 9.—*Tensile strength of plywood and veneer.*

Species.	Number of tests.	Moisture at test (per cent).	Specific gravity * of plywood.	Tensile strength † of 3-ply wood parallel to grain of faces (pounds per square inch).	Tensile strength ‡ of single-ply veneer, $1\frac{1}{2}$ (*d*) (pounds per square inch).
	(*a*)	(*b*)	(*c*)	(*d*)	(*e*)
Ash, black	120	9.1	0.49	6,180	9,270
Ash, commercial white	200	10.2	.60	6,510	9,770
Basswood	200	9.2	.42	6,880	10,320
Beech	120	8.6	.67	13,000	19,500
Birch, yellow	200	8.5	.67	13,200	19,800
Cedar, Spanish	115	13.3	.41	5,200	7,800
Cherry [1]	115	9.1	.56	8,460	12,690
Chestnut	40	11.7	.43	4,430	6,645
Cottonwood	120	8.8	.46	7,280	10,920
Cypress, bald	35	10.3	.47	6,560	9,840
Douglas fir	174	8.7	.49	6,230	9,340
Elm, cork	65	9.4	.62	8,440	12,660
Elm, white	160	8.9	.52	5,860	8,790
Gum, black	35	10.6	.54	6,960	10,445
Gum, cotton	80	10.3	.50	6,260	9,390
Gum, red	182	8.7	.54	7,850	11,775
Hackberry	80	10.2	.54	6,920	10,380
Hemlock, western	119	9.7	.47	6,800	10,200
Magnolia [2]	40	9.9	.59	10,000	15,000
Mahogany, African [3]	20	12.7	.52	5,370	8,060
Mahogany, Philippine [4]	25	10.7	.53	10,670	16,010
Mahogany, true	35	11.4	.48	6,390	9,585
Maple, soft [5]	120	8.9	.57	8,180	12,270
Maple, sugar	202	8.0	.68	10,190	15,290
Oak, commercial red	115	9.3	.59	5,480	8,220
Oak, commercial white	195	9.5	.64	6,730	10,095
Pine, white	40	10.2	.43	5,640	8,460
Poplar, yellow	165	9.4	.50	7,390	11,080
Redwood	65	11.2	.41	5,100	7,650
Spruce, Sitka	103	8.4	.43	5,600	8,400
Sycamore	163	9.2	.56	8,030	12,045
Walnut, black	110	9.1	.59	8,250	12,375

* Specific gravity based on oven-dry weight and volume at test.
† Based on total cross-sectional area.
‡ Based on assumption that center ply carries no load.
Data based on tests of 3-ply panels with all plies in any one panel same thickness and species.
[1] Probably black cherry. [2] Probably evergreen magnolia. [3] Probably khaya sp. [4] Probably tanguile. [5] Probably silver maple.

SAMPLE COMPUTATION.

To obtain the tensile strength of 3-ply wood consisting of two $\frac{1}{20}$-inch birch faces and a $\frac{1}{16}$-inch basswood core.

Parallel to face grain $=2\times\frac{1}{20}\times 19{,}860=1{,}986$ pounds per inch of width.

Perpendicular to face grain $=1\times\frac{1}{16}\times 9{,}450=591$ pounds per inch of width.

This computation neglects the tensile strength of the ply or plies perpendicular to the grain, which is comparatively small. The results are therefore slightly in error.

The resistance to splitting is of considerable importance in panels when these are to be fastened with screws or bolts and are subject to forces at the fastenings. The numerical value of the work required to split a panel of a given thickness has no direct application in design. It is only in comparison with other panels of other species or construction that work in splitting has any significance. The work done is, of course, a measure of resistance to splitting. It is not entirely a property of the wood, as it depends very largely upon the strength of the glue.

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TABLE 10.—*Strength of various species of 3-ply panels.*

All plies in any one panel of the same thickness and of the same species; grain of successive plies at right angles. All material rotary cut. Perkins glue used throughout. Eight thicknesses of plywood, ranging from $\frac{3}{30}$ inch to $\frac{3}{8}$ inch, were tested.

Species.	Average specific gravity of plywood based on oven-dry weight and volume at test.	Average per cent moisture.	Column-bending modulus.				Tensile strength.				Splitting resistance.		Modulus of elasticity.	
			Parallel.*		Perpendicular.*		Parallel.*		Perpendicular.*					
			Number of tests.	Pounds per square inch.	Number of tests.	Pounds per square inch.	Number of tests.	Pounds per square inch.	Number of tests.	Pounds per square inch.	Number of tests.	Per cent of birch.†	Parallel (1,000 pounds per square inch).*	Perpendicular (1,000 pounds per square inch.
Ash, black	0.49	9.1	120	7,760	120	1,779	120	6,180	120	3,940	240	73	1,073	96
Ash, commercial white	.60	10.2	200	9,930	200	2,620	200	6,510	200	4,350	400	71	1,420	143
Basswood	.42	9.2	200	7,120	200	1,670	200	6,880	200	4,300	400	63	1,213	85
Beech	.67	8.6	120	15,390	120	2,950	120	13,000	120	7,290	240	94	2,149	167
Birch, yellow	.67	8.5	195	16,000	200	3,200	200	13,200	200	7,700	400	100	2,259	197
Cedar, Spanish	.41	13.3	115	6,460	115	1,480	115	5,200	115	3,340	230	60	1,032	84
Cherry[a]	.56	9.1	115	12,260	115	2,620	115	8,460	115	5,920	230	80	1,627	152
Chestnut	.43	11.7	40	5,160	40	1,110	40	4,430	40	2,600	80	74	744	75
Cottonwood	.46	8.8	120	8,460	120	1,870	120	7,280	120	4,240	240	85	1,437	109
Cypress, bald	.47	10.3	35	7,830	35	1,820	35	6,560	35	4,390	70	69	1,144	91
Douglas fir	.49	8.7	150	9,460	174	1,950	174	6,230	174	4,000	348	84	1,566	129
Elm, cork	.62	9.4	65	12,710	65	2,500	65	8,440	65	5,500	130	99	1,982	136
Elm, white	.52	8.9	160	8,680	160	1,970	160	5,860	160	3,990	320	75	1,224	109
Gum, black	.54	10.6	40	8,090	40	1,920	35	6,960	35	4,320	70	55	1,275	113
Gum, cotton	.50	10.3	80	7,760	80	1,580	80	6,260	80	3,760	160	60	1,300	111
Gum, red	.54	8.7	182	9,970	182	2,070	182	7,850	182	4,930	364	80	1,592	120
Hackberry	.54	10.2	80	8,100	80	1,880	80	6,920	80	4,020	160	84	1,154	99
Hemlock, western	.47	9.7	119	9,250	119	1,960	119	6,800	119	4,580	238	63	1,581	112
Magnolia[b]	.59	9.9	40	9,830	40	2,340	40	10,000	40	5,740	80	98	1,704	135
Mahogany, African[c]	.52	12.7	20	8,070	20	2,000	20	5,370	20	3,770	......	......	1,261	144
Mahogany, Philippine[d]	.53	10.7	25	10,160	25	2,310	25	10,670	25	5,990	50	90	1,820	169
Mahogany, true	.48	11.4	35	8,500	35	1,940	35	6,390	35	3,780	......	......	1,252	117
Maple, soft[e]	.57	8.9	120	11,540	120	2,420	120	8,180	120	5,380	240	106	1,752	145
Maple, sugar	.68	8.0	202	15,600	202	3,340	192	10,190	202	6,530	404	114	2,112	189
Oak, commercial red	.59	9.3	115	8,500	115	2,070	115	5,480	115	3,610	230	70	1,289	120
Oak, commercial white	.64	9.5	195	10,490	195	2,310	195	6,730	195	4,200	390	85	1,343	118
Pine, white	.43	10.2	35	7,920	40	1,770	40	5,640	40	3,870	80	52	1,274	99
Poplar, yellow	.50	9.4	165	8,860	165	1,920	165	7,390	165	4,720	330	51	1,544	115
Redwood	.41	11.2	65	7,900	65	1,500	65	5,100	65	3,000	130	48	1,211	118
Spruce, Sitka	.43	8.4	103	7,640	103	1,689	103	5,600	103	3,250	206	82	1,395	105
Sycamore	.56	9.2	163	11,040	163	2,340	163	8,030	163	5,220	326	77	1,628	130
Walnut, black	.59	9.1	110	12,660	110	2,770	110	8,250	110	5,260	220	77	1,736	141

* Parallel and perpendicular refer to the direction of the grain of the faces relative to the direction of the application of the force.
† The relative splitting resistance of the various panels tested depends largely on the holding strength of the glue.
[a] Probably black cherry.
[b] Probably evergreen magnolia.
[c] Probably khaya sp.
[d] Probably tanguile.
[e] Probably silver maple.

The results of strength tests on plywood of various common veneer species are given in table 10. Except for birch all tests are on only one shipment of the species, so that the results will in all probability be changed somewhat by the addition of future test data. The mahogany results are on thin plywood ranging in thickness from $\frac{3}{30}$ inch to $\frac{3}{16}$ inch, while the sizes of the plywood for all other species ranged from $\frac{3}{30}$ inch to $\frac{3}{8}$ inch.

In most cases it was found that the column-bending modulus of thin plywood was slightly less than the column-bending modulus of the thick plywood.

TABLE 11.—*Comparison of strength of 3, 5, and 7 ply yellow birch plywood, all plies of same thickness in any one panel.*

Number of plies.	Average specific gravity.*	Average per cent moisture.	Number of tests.	Column-bending modulus, in pounds per square inch. Parallel.†	Column-bending modulus, in pounds per square inch. Perpendicular.†	Tension, in pounds per square inch. Parallel.†	Tension, in pounds per square inch. Perpendicular.†	Average splitting resistance compared to 3-ply birch, for the same plywood thickness, in per cent of 3-ply.
3	0.67	8.5	195	16,000	3,200	13,200	7,700	100
5	.67	6.6	25	14,700	6,800	13,100	8,600	129
7	.70	7.1	25	14,300	7,900	12,900	9,300	191

* Specific gravity, based on oven-dry weight and volume at test.
† Parallel and perpendicular refer to direction of grain of faces relative to direction of application of force.

Table 11 shows the decrease in the unit strength of plywood in the direction of the grain of the faces when the number of plies is increased, and the increase in the unit strength of plywood perpendicular to the grain of the faces when the number of plies is increased.

TABLE 12.—*Comparison of strength of three-ply wood having a core of high density with similar plywood having a core of low density of the same thickness; each ply $\frac{1}{20}$ inch thick.*

Number of tests very limited. Results tabulated will probably be changed by further tests.

Species. Face.	Species. Core.	Species. Face.	Number of tests.	Plywood thickness	Per cent moisture at test.	Specific gravity, based on oven-dry weight and volume at test.	Column-bending modulus in pounds per square inch. Parallel.*	Column-bending modulus in pounds per square inch. Perpendicular.*	Tension in pounds per square inch. Parallel.*	Tension in pounds per square inch. Perpendicular.*	Maximum unit load in pounds per square inch, 5 by 12 inch specimen tested as a column. Parallel.*	Maximum unit load in pounds per square inch, 5 by 12 inch specimen tested as a column. Perpendicular.*
				Inches.								
Birch........	Birch...........	Birch.......	30	0.15	9.4	0.68	14,200	3,170	11,900	7,290	258	21
Do.....	Basswood.......	...do.......	10	.14	8.2	.61	15,200	1,600	12,900	3,800	250	12
Sugar maple	Sugar maple....	Sugar maple	33	.15	6.9	.69	16,100	3,210	9,910	6,540	265	45
Do.......	Basswood.......	...do.......	5	.15	7.0	.62	17,700	2,600	12,000	3,700	247	15
Red gum...	Red gum.......	Red gum...	20	.14	9.5	.55	9,550	2,060	8,410	4,720	193	35
Do.......	Basswood.......	...do.......	5	.15	8.3	.44	7,200	1,400	4,900	3,000	115	11
Do.......	Yellow poplar..	...do.	5	.14	6.5	.51	10,100	....	6,200	4,500	149	17

* Directions refer to direction of application of the force relative to the grain of the faces.

Table 12 shows that the strength values of plywood parallel to the grain of the faces are practically the same for three-ply wood having a core of dense wood as for plywood having a core of light wood. The strength values across the grain of the faces are, however, very much

less for the plywood with core of low density. In other words, the strength values of three-ply wood parallel to the grain of the faces are almost entirely determined by the strength values of the face material, and the strength values across the grain of the faces are very largely determined by the strength values of the core species.

Table 13 gives a number of factors that are of value in selecting the thickness and species of the plies for a three-ply panel.

TABLE 13.—*Thickness factors for veneer.*

Giving: (1) Veneer thickness for the same total bending strength as birch; (2) veneer thickness for the same weight as birch.

Species.	D. Average specific gravity of species * based on oven-dry weight and air-dry volume.	Specific gravity of glued plywood as tested.	Per cent moisture of plywood as tested.	S. Per cent unit bending strength compared with birch.†	K_s. Thickness factor for the same total bending strength as birch, $\sqrt{\frac{100}{S}}$.	K_w. Thickness factor for the same weight as birch, $\frac{0.63}{D}$.
Ash, black	0.50	0.49	9.1	52	1.39	1.26
Ash, commercial white	.58	.60	10.2	72	1.18	1.09
Basswood	.38	.42	9.2	48	1.44	1.66
Beech	.63	.67	8.6	94	1.03	1.00
Birch, yellow	.63	.67	8.5	100	1.00	1.00
Cedar, Spanish	[a].34	.41	13.3	43	1.52	1.85
Cherry [b]	.51	.56	9.1	80	1.12	1.24
Chestnut	.44	.43	11.7	34	1.72	1.43
Cottonwood	.43	.46	8.8	56	1.34	1.47
Cypress, bald	.44	.47	10.3	53	1.37	1.43
Elm, cork	.66	.62	9.4	78	1.13	.95
Elm, white	.51	.52	8.9	58	1.31	1.24
Fir, Douglas	[c].51	.49	8.7	60	1.29	1.24
Gum, black	.52	.54	10.6	56	1.34	1.21
Gum, cotton	.52	.50	10.3	48	1.44	1.21
Gum, red	.49	.54	8.7	64	1.25	1.29
Hackberry	.54	.54	10.2	55	1.35	1.17
Hemlock, western	.42	.47	9.7	60	1.29	1.50
Magnolia	.51	.58	9.9	67	1.22	1.24
Mahogany, African	[a].46	.52	12.7	56	1.34	1.37
Mahogany, Philippine [d]	[a].57	.53	10.7	68	1.21	1.10
Mahogany, true	[a].49	.48	11.4	57	1.32	1.29
Maple, soft [e]	.48	.57	8.9	74	1.16	1.31
Maple, sugar	.62	.68	8.0	100	1.00	1.02
Oak, commercial red	.63	.59	9.3	59	1.30	1.00
Oak, commercial white	.69	.64	9.5	69	1.20	.91
Pine, white	.39	.43	10.2	52	1.38	1.61
Poplar, yellow	.41	.50	9.4	58	1.31	1.54
Redwood	[a].36	.41	11.2	49	1.43	1.75
Sycamore	.50	.56	9.2	71	1.09	1.26
Spruce, Sitka	.38	.43	8.4	50	1.41	1.66
Walnut, black	.57	.59	9.1	83	1.10	1.10

* Taken from Bulletin 556 of the U. S. Department of Agriculture.
† Average of the column-bending moduli parallel and perpendicular to grain compared to birch.
[a] Based on subsequent tests.
[b] Probably black cherry.
[c] Coast type Douglas fir.
[d] Probably tanguile.
[e] Probably silver maple.

The thickness factor (K_s) is used to obtain the thickness of a ply of any species having the same total bending strength as a given ply of birch. It is arrived at as follows:

The strength of any structural member is determined either by the direct load it can sustain or the bending moment it can resist without failure. In plywood the latter factor is the better criterion of strength. If we denote the maximum bending moment of a strip of

three-ply wood 1 inch wide and of thickness d_1 by M_1 and the stress at failure by S_1 (column-bending modulus), then $M_1 = \frac{S_1 d_1^2}{6}$.

Similarly, the strength of another strip of a different species will be denoted by M_2, its stress at failure S_2, and thickness d_2. By a proper selection of thickness d_2 the second strip may be made to withstand the same maximum bending moment, so that $M_2 = M_1$ or $S_2 d_2^2 = S_1 d_1^2$. From this the desired thickness $d_2 = d_1 \sqrt{\frac{S_1}{S_2}}$. Taking d_1 as the unit of thickness of a birch plywood strip and expressing the maximum stresses in percentage of birch, we have $d_2 = \sqrt{\frac{100}{S_2}}$, or, in general, $K_s = \sqrt{\frac{100}{S}}$, where K_s is the thickness of the plywood, whose column-bending modulus corresponds to S and whose total bending strength, given by the bending moment, is the same as that of birch plywood of thickness unity.

The same reasoning also applies to single plies, so that K_s may be used to get the thickness of a single ply, which will give the same total bending strength as a birch ply of thickness unity. For example, for yellow poplar $K_s = 1.46$, and a ply of this species, $1.46 \times \frac{1}{16} = 0.091$ inch, is equivalent in strength in bending to a birch ply $\frac{1}{16}$ inch thick.

By way of explanation it must be understood that unit bending strength refers to a maximum stress such as the modulus of rupture, or the column-bending modulus, while total bending strength refers to the load or bending moment a beam can sustain or the bending moment a column can sustain.

It should be kept in mind that these factors will doubtless be modified somewhat by further tests.

The thickness factor (K_w) is used to obtain the thickness of a ply of any species equal in weight to a ply of yellow birch of given thickness. It is obtained by simply dividing the density of birch by the density of the species for which the thickness is desired. The density data used in computing K_w are the same as that given in United States Department of Agriculture Bulletin 556, "Mechanical Properties of Woods Grown in the United States." The weight of the glue in the plywood is neglected.

For yellow poplar, for example, the thickness of a ply equal in weight to a $\frac{1}{16}$-inch ply of birch is $1.54 \times \frac{1}{16} = 0.096$ inches.

The column-bending tests, upon which the data in table 10 are based, were all made on specimens of the same lengths, and it was felt desirable to determine what effect, if any, the change in length of the column might have upon the maximum unit load, the slenderness ratio remaining constant. Special panels of three-ply birch, all plies of the same thickness in each panel, were made up from veneer of the following thicknesses: $\frac{1}{30}$, $\frac{1}{24}$, $\frac{1}{20}$, $\frac{1}{16}$, $\frac{1}{10}$, $\frac{1}{8}$, and test columns varying in length from 20 inches to 6 inches were cut from them and tested. The conclusion drawn from these tests is that for a given slenderness ratio the length of the column has little, if any, effect on the maximum unit load which a three-ply birch column will sustain. It is assumed that the same conclusion will apply to panels of other species.

Table 9, to which reference has already been made, presents data by which it is possible to calculate the strength in tension of plywood composed of various kinds of veneer. Column (*d*) of this table is identical with the corresponding column in table 10. Column (*c*) is to be used in calculating the strength in tension of plywood made up of different species. The method of calculation is based upon the fact that the tensile strength of wood in a direction perpendicular to the grain is very small in comparison with that parallel to the grain and

may, therefore, for purposes of approximation, be neglected. To obtain the tensile strength in any direction, simply add together the tensile strength, parallel to the grain, of the individual plies the grain of which lies parallel to the direction in which the strength is desired. The sample computation will make this entirely clear.

The shearing strength of plywood is of importance in connection with the design of box beams having plywood cheek pieces and for similar construction. Several series of tests are under way to determine the shearing strength of plywood of various thicknesses when unsupported for various distances. While these tests are not as yet completed, it is evident that it will not be possible to use a shearing strength in calculating these members much greater than that of solid wood of the same species. There is much more residual strength in plywood after the first failure than in solid wood, and for this reason a somewhat higher working stress would be justified. Until more data are available the shear allowed in plywood should not be over 25 per cent greater than that allowed in solid wood of the same species. This assumes that in the cheeks of horizontal beams the face plies will be vertical, a condition dictated by experience to be best practice.

RIVETED JOINTS IN PLYWOOD.

The matter of joints in plywood is of the greatest importance in connection with the construction of various types of built-up structures such as fuselages, boat hulls, pontoons,

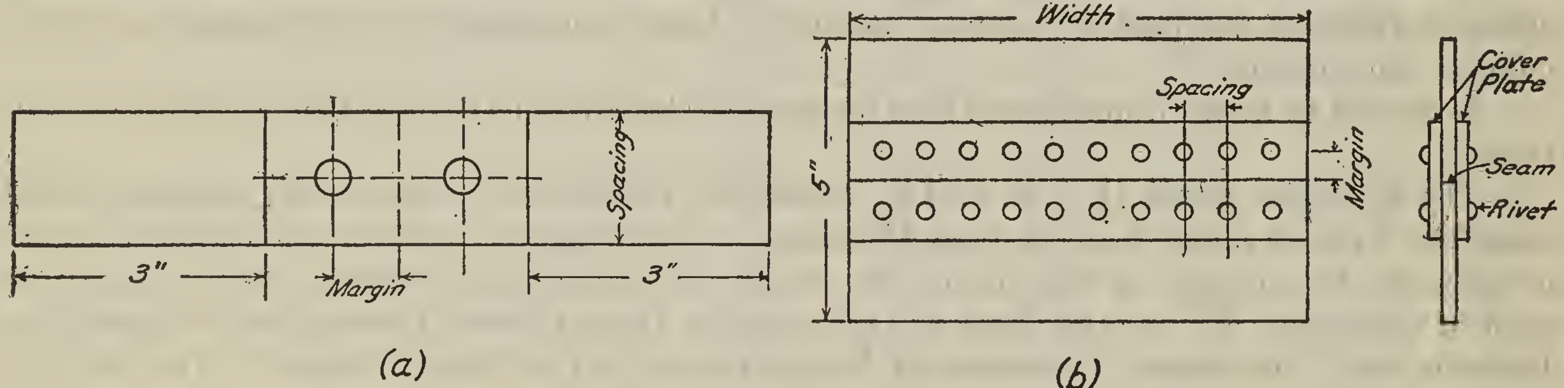

Fig. 30.—(a) Test specimen for single-rivet tests. (b) Test specimen for multiple-rivet tests.

and beams and girders. Several series of tests have been made to determine the efficiency of various types of joint for different kinds of loading.

The first series of tests was made upon riveted joints designed for tension and compression. The tests were all made in tension; both solid and hollow rivets were used. Two types of test were run; most of the tests were made on specimens only wide enough to accommodate one rivet (fig. 30a), and later enough wide specimens were tested (fig. 30b) to verify the assumption that the data on the narrow specimens could be applied without correction to wider ones.

In general, most of the tests were made on butt joints, with straps on each side. In some cases the straps were of plywood and in others of galvanized sheet metal about 0.02 inches thick. The nomenclature used will become clear upon examination of figure 30.

The first tests were made upon red gum plywood composed of three plies of $\frac{1}{16}$ material, riveted with solid copper rivets through sheet-metal cover plates. The grain of the face plies was perpendicular to the seam. Figure 31 shows the strength of the joint with varying margins and spacing. It is apparent that the best conditions are obtained with a 1-inch margin and a one-half inch spacing.

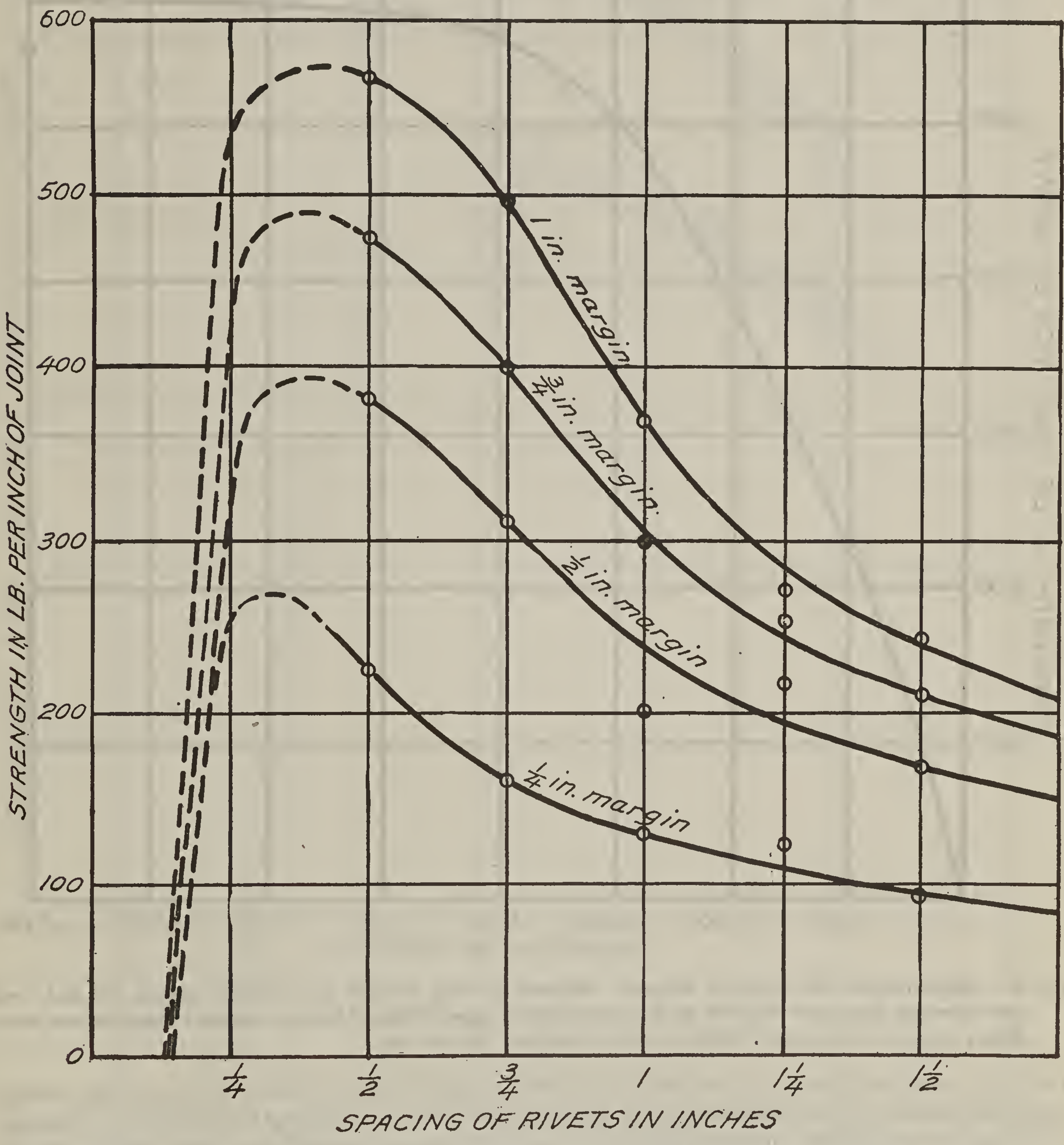

Fig. 31.—Single-riveted butt joints in plywood. Relations among strength, margin, and spacing: Red gum plywood, plies 1/16 by 1/16 by 1/16 inch; solid copper rivets, 0.15 inch diameter; sheet-metal cover plates; grain of faces perpendicular to seam; moisture, 7.4 per cent.

Figure 32 shows the variation of strength when using a constant spacing of one-half inch and margins varying from one-quarter inch to 2 inches. This figure shows very clearly that no appreciable additional strength can be obtained by increasing the margin above 1 inch.

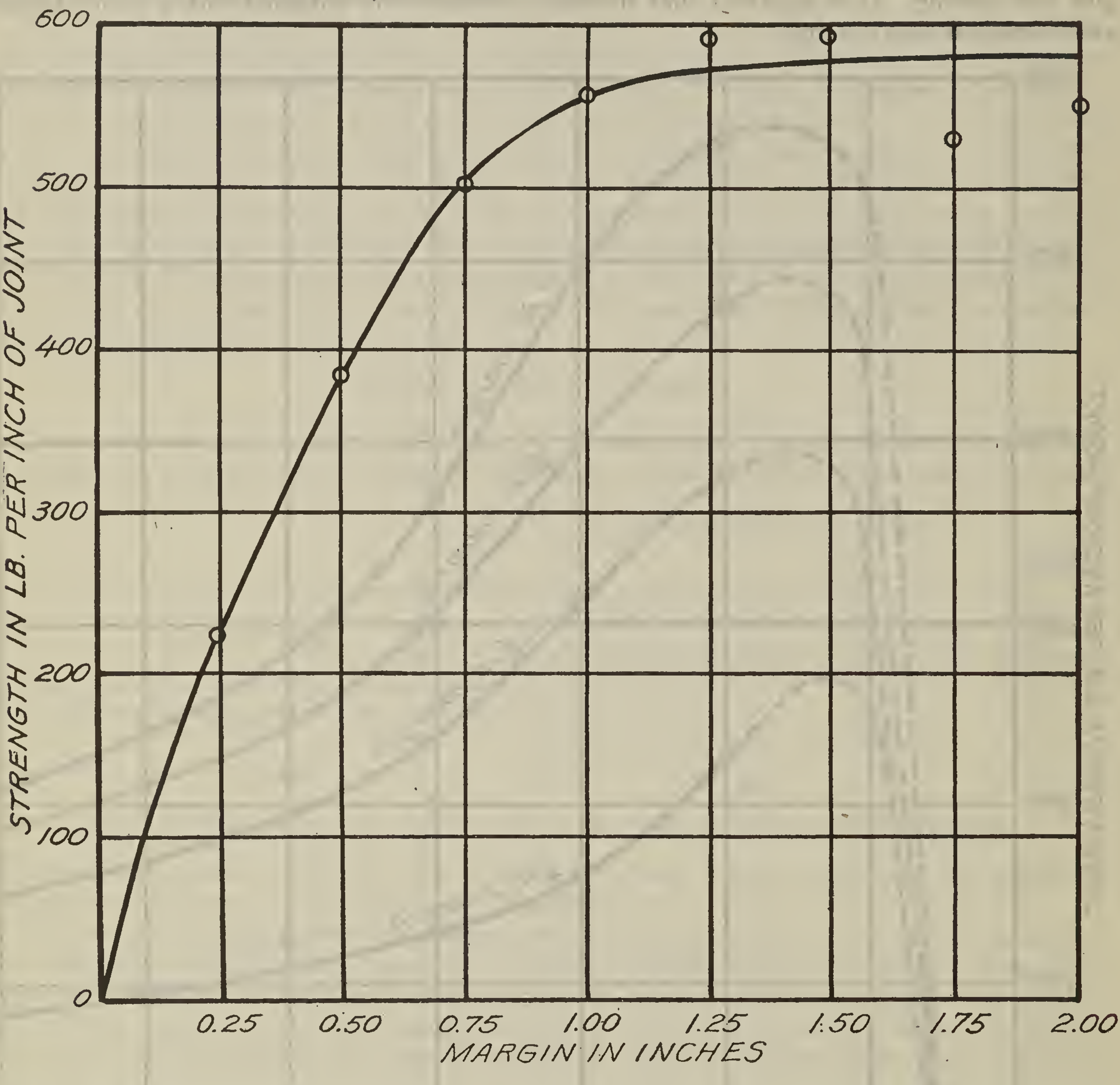

Fig. 32.—Single-riveted butt joints in plywood. Relation between strength and margin: Spacing 1/2 inch; red gum plywood, plies 1/16 by 1/16 by 1/16 inch; solid copper rivets, 0.15 inch diameter; sheet-metal cover plates; grain on faces perpendicular to seam; moisture, 7.4 per cent.

In fact, it was found that in case the grain of the face plies was parallel to the seam, the margin could be reduced to three-quarters inch without sacrificing an appreciable amount of strength.

Similar tests made on three-ply birch, each ply one-sixteenth inch, gave similar results, as shown in figures 33 and 34. With a margin of $1\frac{1}{2}$ inches, the maximum strength was secured with a spacing of one-half inch.

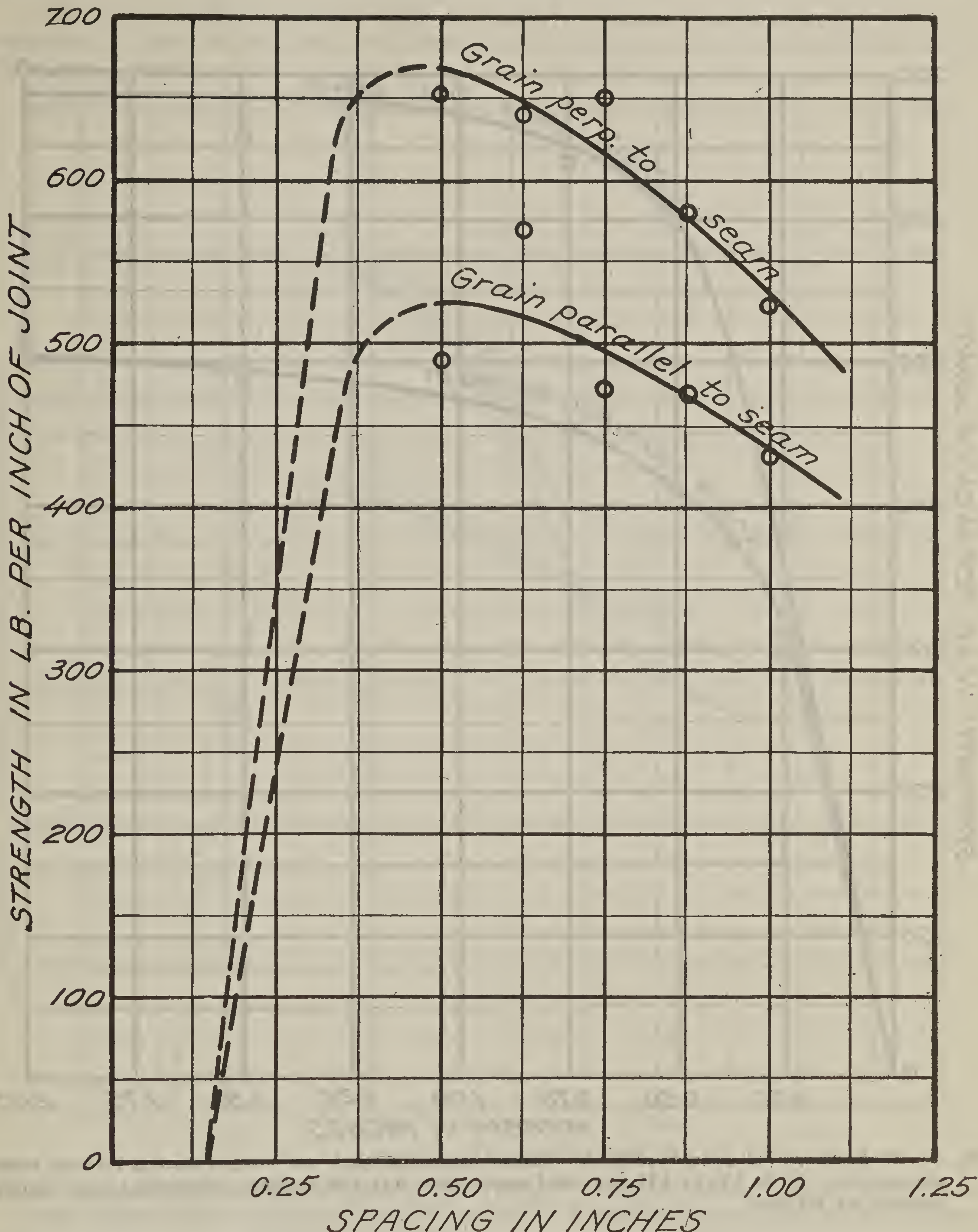

Fig. 33.—Single-riveted butt joints in plywood. Relation between strength and spacing: Margin, 1 1/2 inches; birch plywood, plies 1/16 by 1/16 by 1/16 inch; solid copper rivets, 0.15 inch diameter; sheet-metal cover plates; moisture, 6.6 per cent.

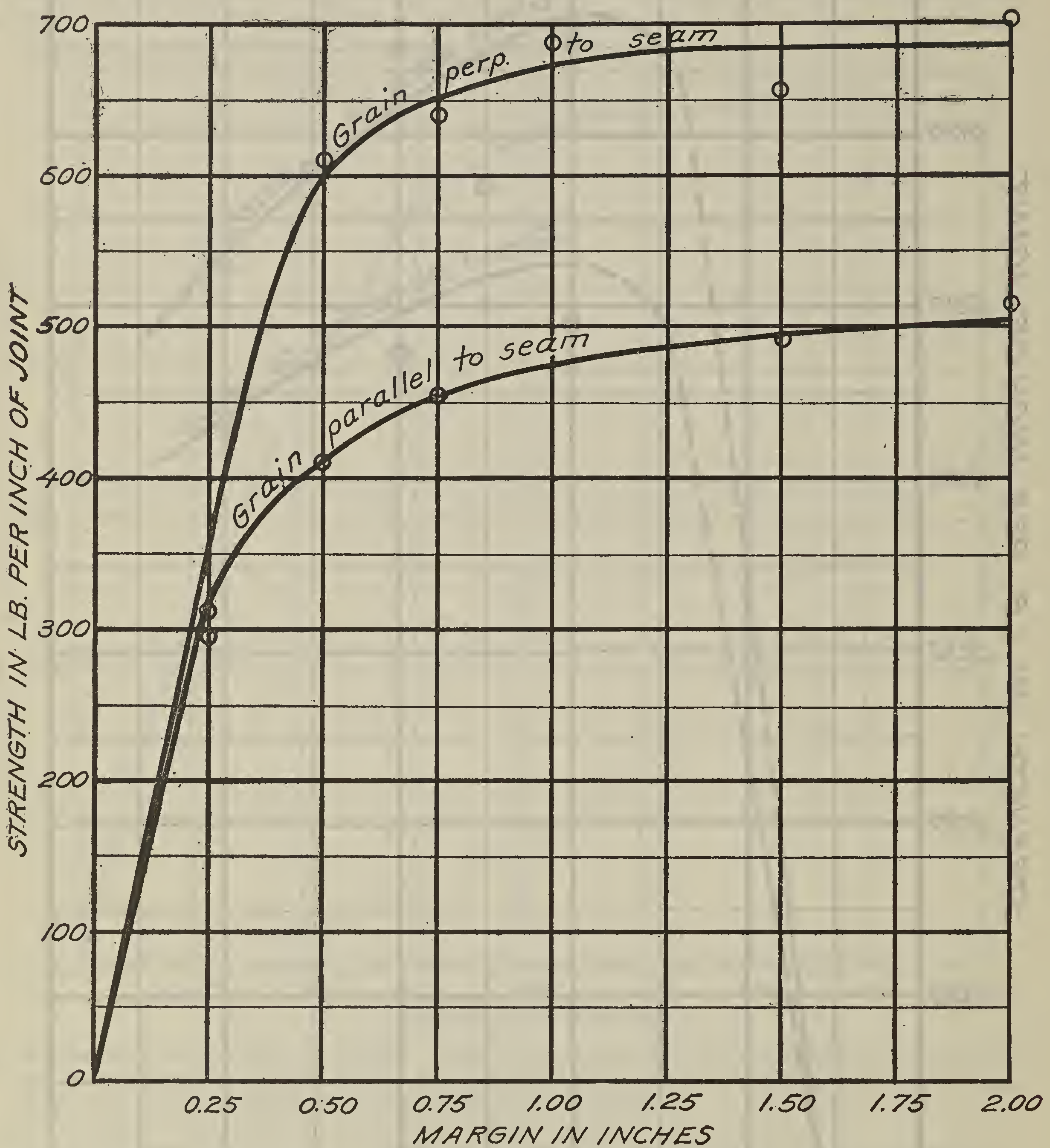

Fig. 34.—Single-riveted butt joints in plywood. Relation between strength and margin; spacing, 1/2 inch; birch plywood, plies 1/16 by 1/16 by 1/16 inch; solid copper rivets, 0.15 inch diameter; sheet-metal cover plates; moisture, 6.6 per cent.

The margin could have been reduced to 1 inch or even less without a great falling off in efficiency. Figure 35 indicates that a spacing of one-half inch is the best with thinner birch (each ply $\frac{1}{20}$ inch).

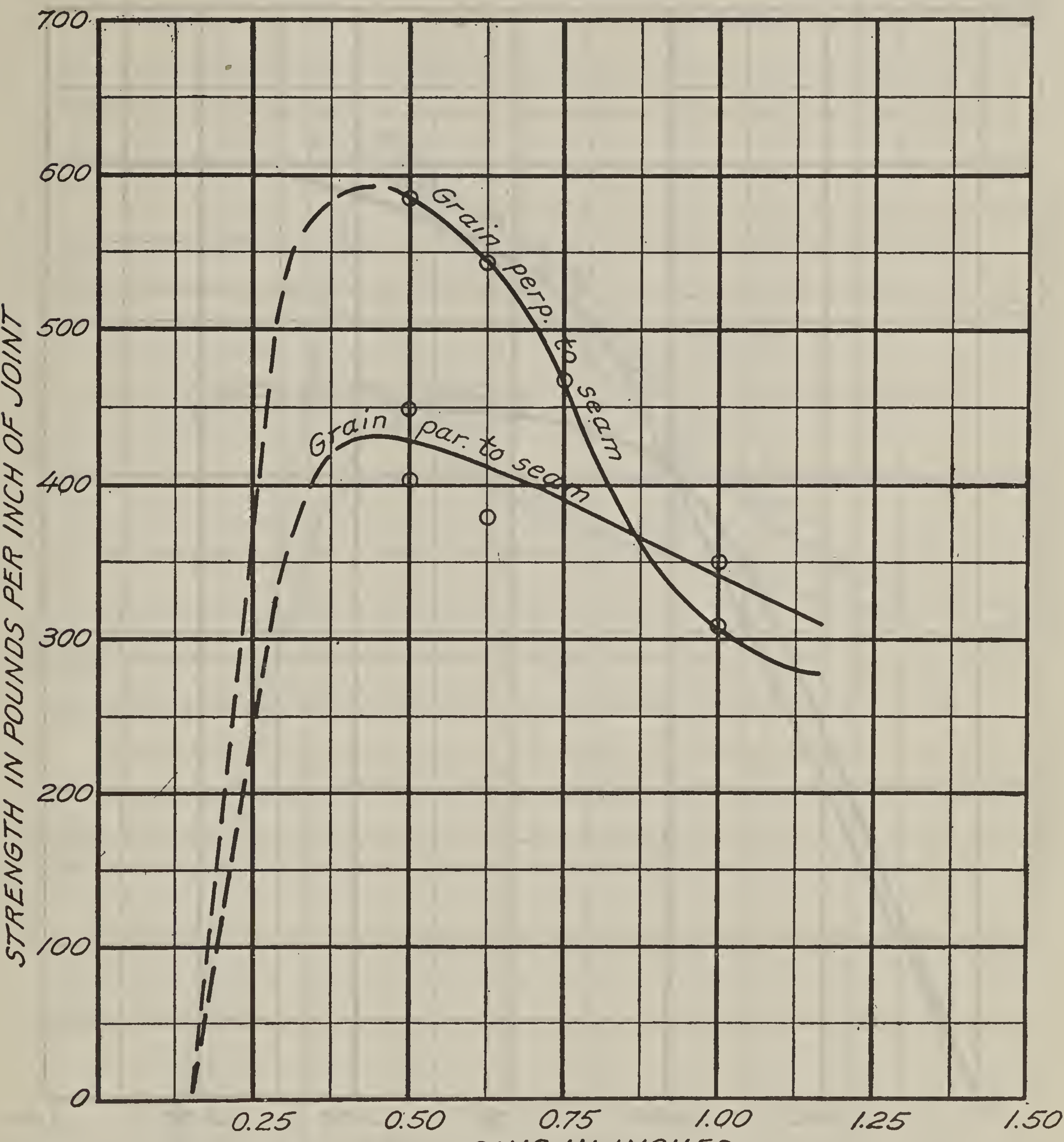

Fig. 35.—Multiple-riveted butt joints in plywood; relation between strength and spacing; test joint, 5 to 5 1/2 inches wide; margin, 1 inch; birch plywood, plies 1/20 by 1/20 by 1/20 inch; solid copper rivets, 0.15 inch diameter; sheet-metal cover plates; moisture, 5.6 per cent.

Figures 36 and 37 show the strength of joints made in three-ply birch (each ply one-twentieth of an inch) with five-eighths-inch hollow aluminum rivets and plywood cover plates. A spacing of 1¼ inches gave the best efficiency with a margin of 2 inches. It is possible that

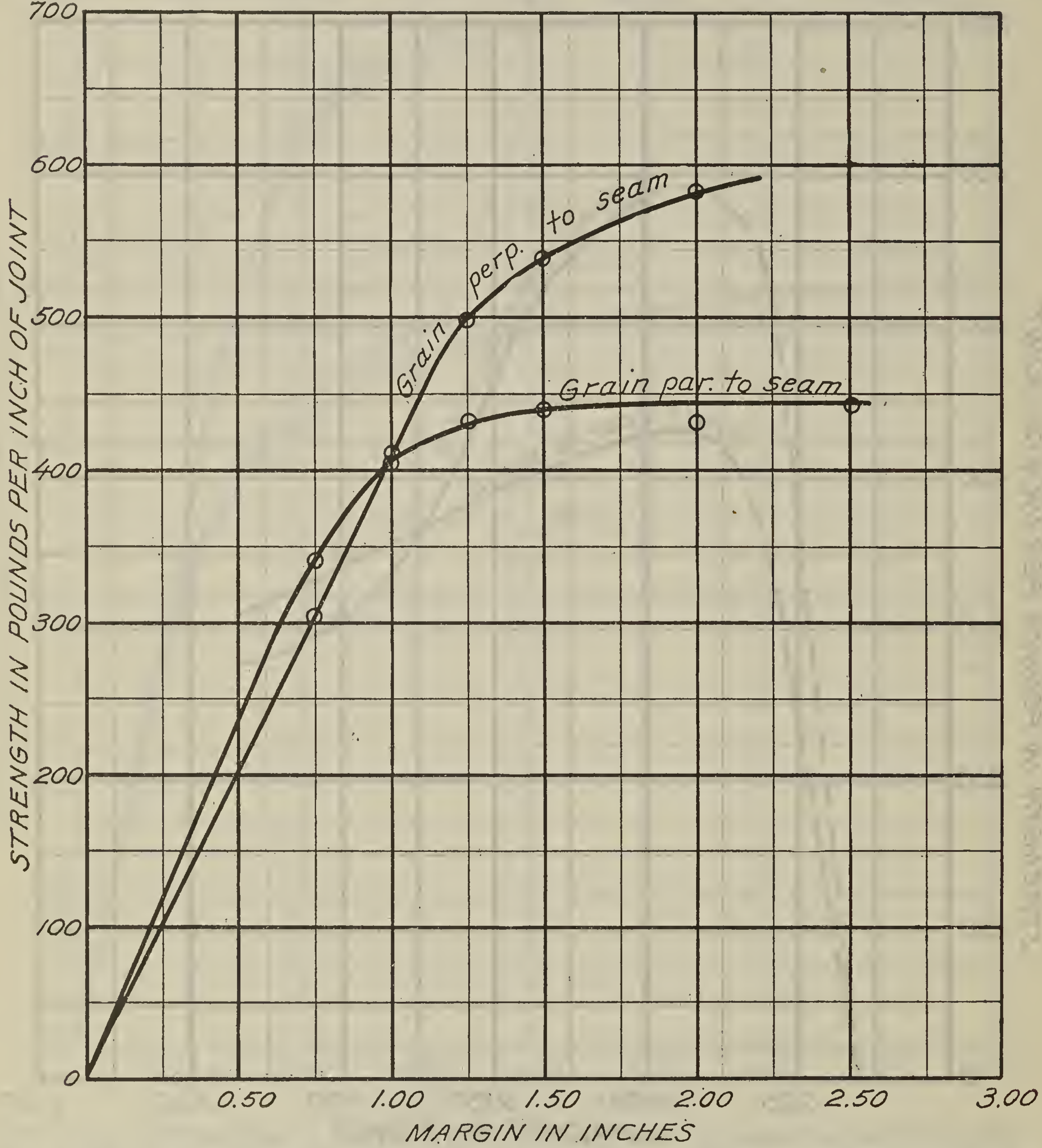

Fig. 36.—Single-riveted butt joints in plywood; relation between strength and margin; spacing, 1.25 inches; birch plywood, plies 1/20 by 1/20 by 1/20 inch; hollow aluminum rivets, 5/8 inch outside diameter; plywood cover plates; moisture, 5.6 per cent.

greater strength could have been secured in the case of the specimens with the grain of the faces perpendicular to the seam had a greater margin than 2 inches been used. In the case of the specimens with the grain of the faces parallel to the seam a margin of 1¼ inches could have been used without any great reduction in strength.

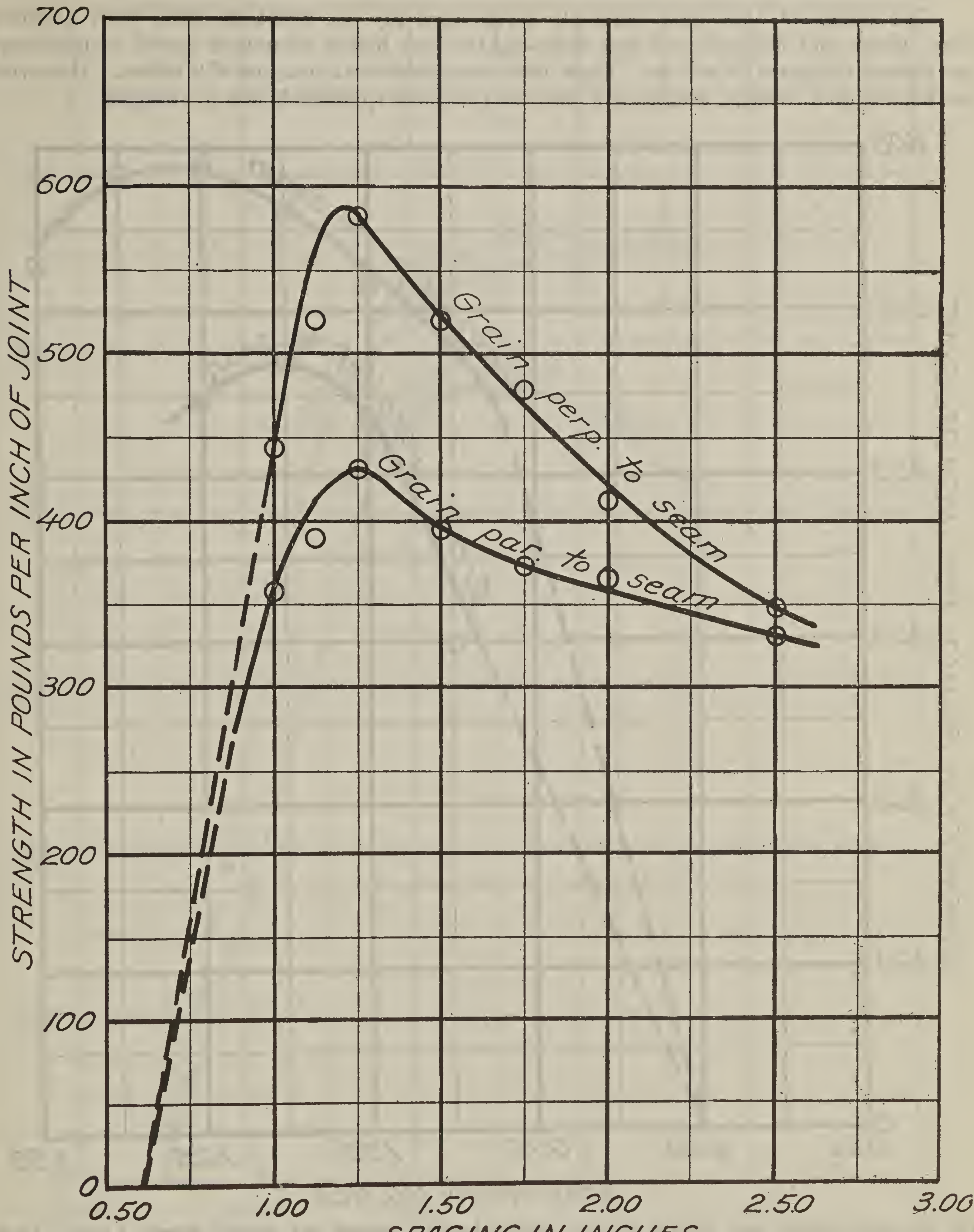

Fig. 37.—Single-riveted butt joints in plywood; relation between strength and spacing; margin, 2 inches; birch plywood, plies 1/20 by 1/20 by 1/20 inch; hollow aluminum rivets, 5/8 inch outside diameter; plywood cover plates; moisture, 5.6 per cent.

The results of tests upon three-ply birch (each ply one-twentieth inch) with plywood cover plates and one-half inch and three-eighths inch hollow aluminum rivets, respectively, are plotted in figures 38 and 39. These tests were made with margins of 2 inches. However, smaller margins could no doubt have been used without appreciable loss in strength.

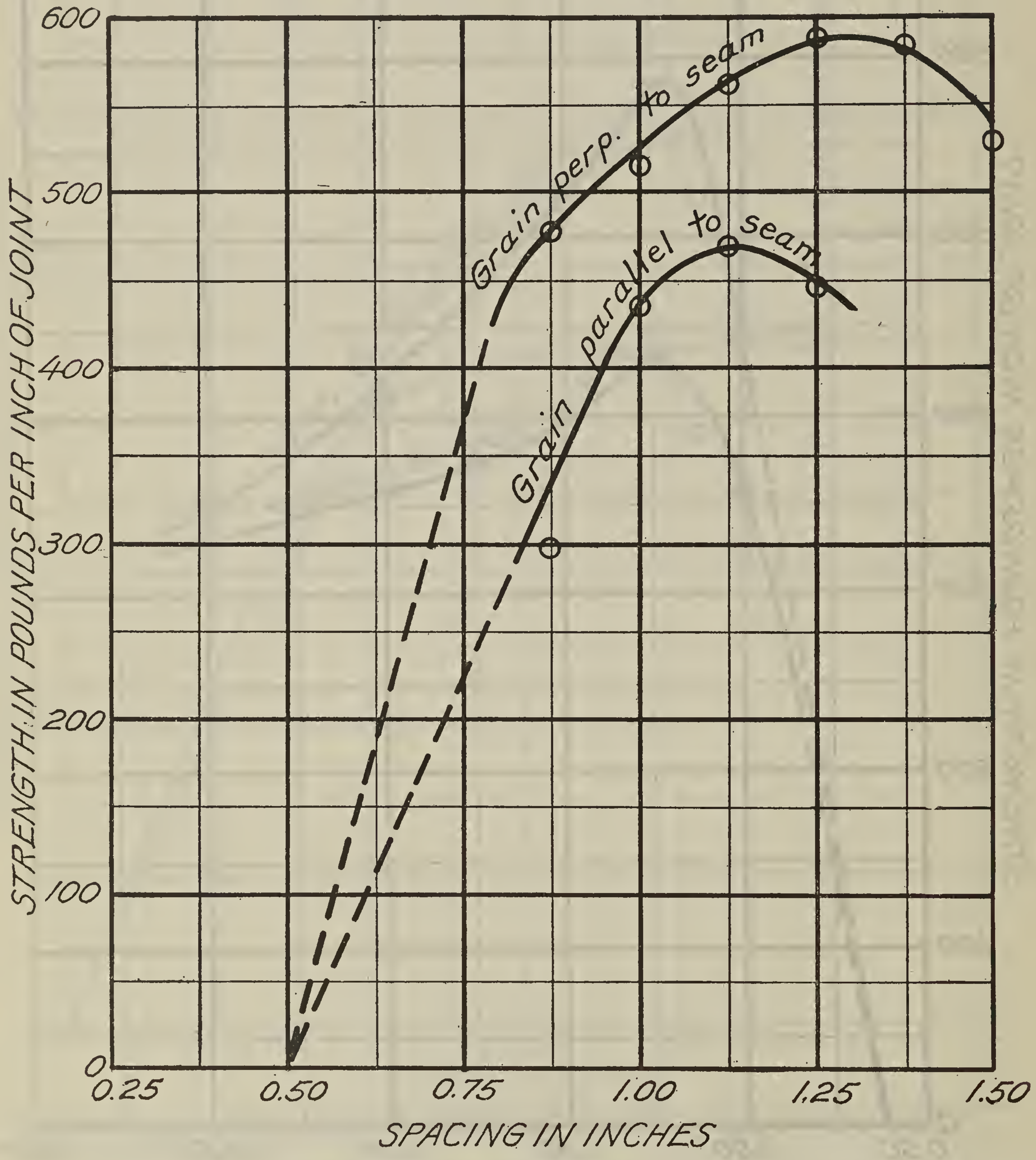

Fig. 38.—Single-riveted butt joints in plywood; relation between strength and spacing; margin, 2 inches; birch plywood, plies 1/20 by 1/20 by 1/20 inch; hollow aluminum rivets, 1/2 inch outside diameter; plywood cover plates; moisture, 5.6 per cent.

Fig. 39.—Single-riveted butt joints in plywood; relation between strength and spacing; margin, 2 inches; birch plywood, plies 1/20 by 1/20 by 1/20 inch; hollow aluminum rivets, 3/8 inch outside diameter; plywood cover plates; moisture, 5.6 per cent.

When the most efficient spacing and margin are used, there is practically no difference in strength for the different sizes of rivets investigated. However, the smaller rivets require a smaller spacing and therefore more labor in manufacture. On the other hand, the margin required is less than in the case of the larger rivets, and this may in some cases be a decided advantage.

Cover plates may be of metal or plywood, as preferred. If of metal, aluminum sheet about three-sixty-fourths inch or one-sixteenth inch thick is recommended for the thicknesses of plywood investigated.

The efficiency of the joints was determined by testing a number of samples of the plywood, both parallel and perpendicular to the face plies, and it was determined that under the best conditions the efficiency of the joints with the face plies perpendicular to the seam was about 30 per cent, while with the face plies parallel to the seam the maximum efficiency was a little over 50 per cent.

While riveted joints may be satisfactory under certain circumstances, they can not be used where an efficiency much over 50 per cent is required. In these cases it is necessary to use glued joints, of which there are several different types.

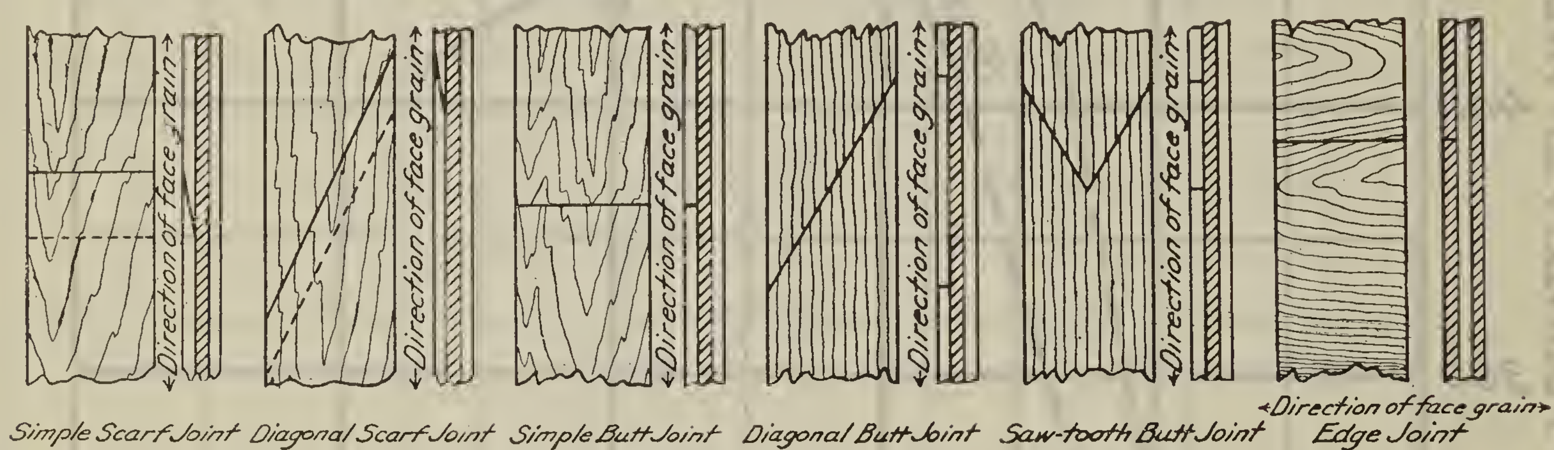

Fig. 40.—Joints in the face veneer of three-ply wood.

JOINTS IN INDIVIDUAL PLIES.

Joints in individual plies may be made in a variety of ways. Figure 40 shows several possible methods for joining pieces of veneer. A considerable number of strength tests upon several of these joints have been made. The simple scarf joint has been tested for a long range of slopes of scarf. The diagonal scarf joint, as well as the diogonal butt joint, have been tested for various slopes of the diagonal. The saw-tooth butt joint has been tested for various angles of the saw tooth.

In balancing up the various factors of strength, ease of manufacture, and efficiency it was decided that the simple scarf joint is the most desirable of the group. The simple butt joint should not be used where strength is important. The edge joint is satisfactory if carefully made. The slope of the scarf in the simple scarf joint should be within the range of from 1 to 20 to 1 to 30.

In comparison with the use of rivets, joints in individual plies are probably more practical. They have an advantage, too, in that the joints in the plies of a given panel may be staggered, so that any defect that may occur in any particular joint only partially weakens the entire panel. The time and labor involved in the preparation of this type of joint, while probably less than the time and labor involved in the preparation of riveted joints, is greater than that in preparing the scarf joint extending through the entire thickness of the panel.

JOINTS EXTENDING THROUGH THE ENTIRE THICKNESS OF PLYWOOD.

Many tests have been made upon scarf joints extending through the entire thickness of a panel. Such joints were prepared by various manufacturers using different glues, different combinations of veneer thicknesses and species, and various slopes of scarf. Two types of scarf joints extending through the entire plywood thickness have been tested and are here described as the straight scarf joint and the Albatros scarf joint. The two types are shown in figure 41. The tests indicate quite conclusively that the straight scarf joint is the superior joint of the two. An examination of the Albatros joint will show that the face ply of the one panel does not meet the face ply of the second panel or only partially meets it. In place of being glued to wood that has the grain running in the same direction, the face ply of one panel is glued to the core of the second panel, in which the grain runs at right angles to the grain in the face. Joints in which the grain of the two pieces joined is at right angles are not as strong as joints in which the grain of the two pieces is parallel.

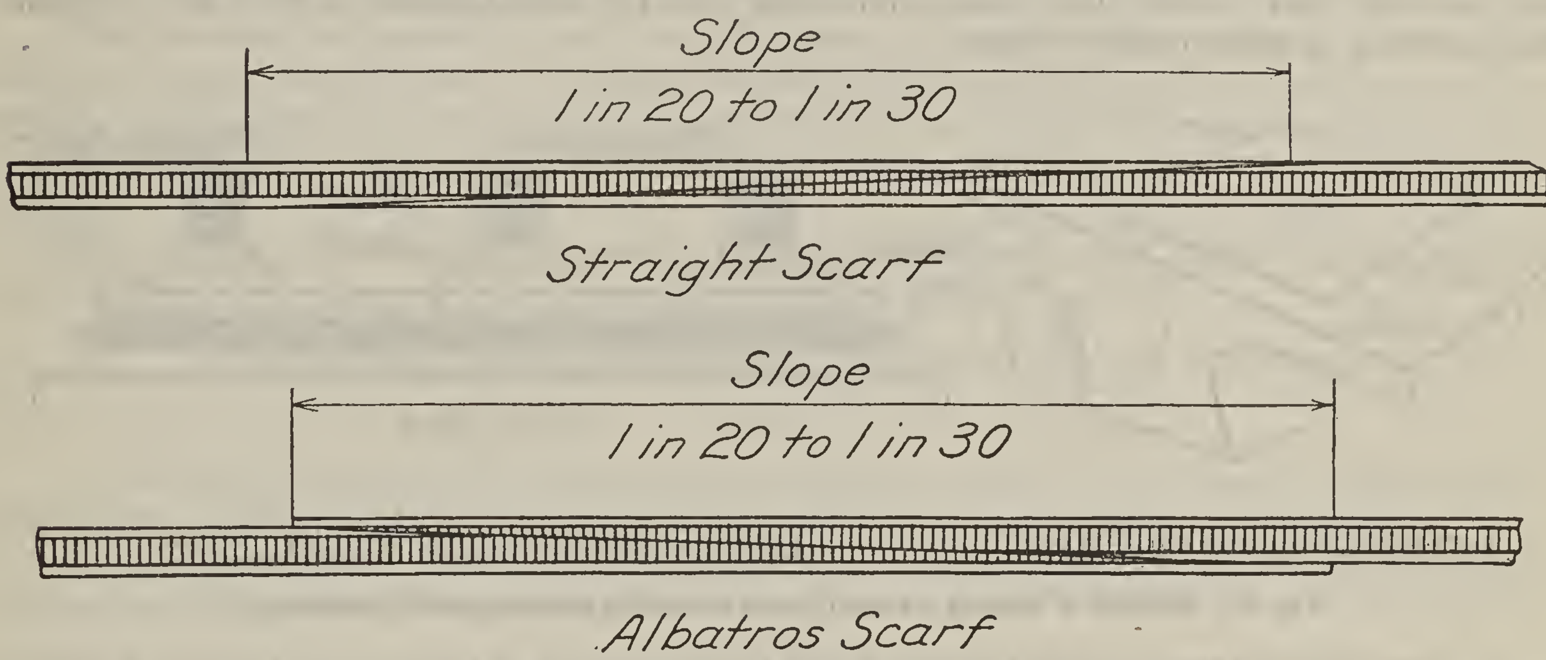

Fig. 41.—Joints in plywood extending through the entire thickness.

Tension tests on the straight scarf joint show that an efficiency of over 90 per cent may be obtained with this type of joint for a slope of scarf as low as 1 in 10. On account of the variations in the effectiveness of the gluing by different manufacturers, it is recommended that a slope of scarf greater than this be used. A slope in the neighborhood of 1 in 25, with a range of from 1 in 20 to 1 in 30, is recommended.

Severe weakening of scarf joints is often due to sanding of the face plies at the joint. Observations on joints of this kind that were sanded showed that at times more than half of the face ply is ground away. Inasmuch as the strength of a panel lies almost entirely in the face plies (in case of three-ply panels parallel to the direction of the grain of the faces), it is obvious that a reduction in the thickness of the face plies will materially affect the strength of a panel. Consequently it is recommended that if the scarf joint is sanded at all that it be only lightly sanded by hand, so as not to decrease the thickness of the face veneer.

Figure 42 shows the method used for cutting the scarf and for gluing the two pieces of plywood together. The board above the panel should be relatively massive and flat so as to distribute the pressure from the screws. Two or three layers of blotting paper furnish sufficient padding to accommodate irregularities in the surface.

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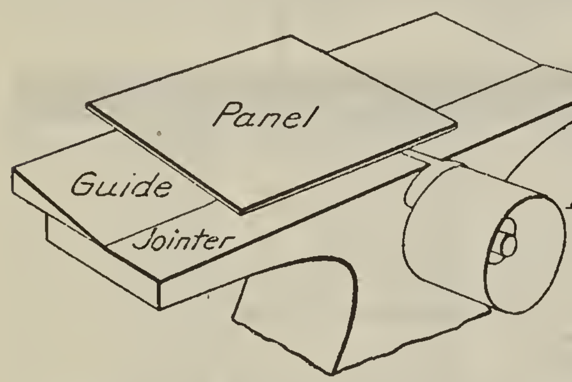
THIN PLYWOOD.

In an effort to develop a substitute for linen for wing covering which could be used on present types of wing framework, several different kinds of thin plywood have been developed. Among these are plywoods composed of three plies of wood, each ply as thin as one one-hundred-and-tenth inch, plywoods with veneer faces and fabric cores, plywoods with veneer faces and metal wire core, plywoods with veneer core and cloth faces, and several other types. A method was developed which made it commercially possible to glue up very thin plywood without undue loss, although the losses in making thin plywood are naturally much greater than in making comparatively thick plywood on account of the fragile nature of the thin sheets and their tendency to warp and twist when glue is applied to them. It was not found possible to produce a plywood having all the requisite properties which was as light as doped linen. The general conclusions drawn from the investigation follow:

1. Spanish cedar, mahogany, birch, sugar maple, red gum, yellow poplar, black walnut, and basswood may be cut into veneer sufficiently thin for consideration in plywood air-plane wing covering as substitutes for linen.



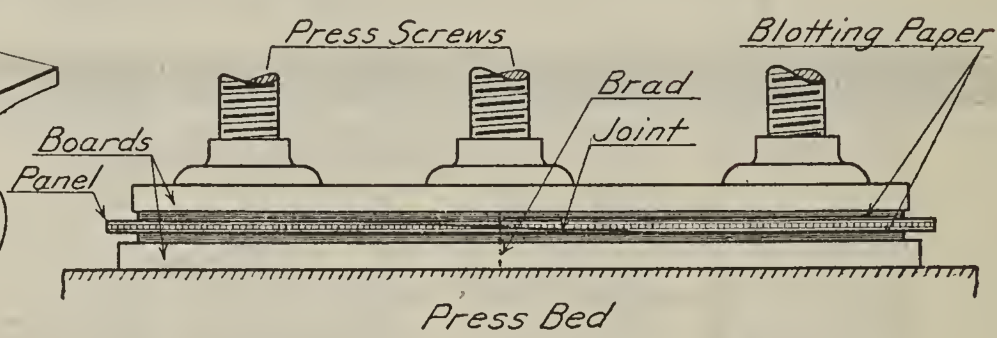


Fig. 42.—Method of making plywood joints extending through entire thickness.

2. These species may be glued satisfactorily by the method of introducing the glue between the plies by means of tissue paper previously coated with glue.

3. It does not seem that plywood sheets of the same weight per square foot as doped linen can be prepared on a practical scale.

4. Covering made either of veneer or of a combination of veneer with fabric, such as linen, cotton, wire screening, or kraft paper, in order to be both practical from the point of view of manufacture and satisfactory in mechanical properties as shown by test, weighs from two to three times as much as doped linen.

5. Plywood that might be considered practical from the point of view of manufacture possesses from two to three times the tensile strength of doped linen.

6. The thinnest ply-wood that can be manufactured at present with any degree of facility (3 plies of one one-hundred-and-tenth inch Spanish cedar) lacks toughness and tearing strength.

7. In general the tearing strength of a practical thin plywood covering is considerably higher than that of doped linen, while its resistance to blows as indicated by the toughness test is lower.

8. In order to obtain the requisite degree of toughness, it is necessary to introduce a cloth fabric into the construction. Grade A cotton now in use in airplane construction is satisfactory for this purpose.

9. Combinations of veneer with kraft paper developed satisfactory tensile strength, but are low in toughness. They compared favorably with linen in tearing resistance.

10. Combinations of veneer with light wire screening, thus far tested, are heavy and unsatisfactory from the point of view of tensile strength per unit weight. Their toughness and tearing resistance are not superior to cloth when used in combination with veneer.

11. Thin plywood or a combination of veneer with cloth is more rigid than linen.

12. Thin plywood unprotected by a finish changes moisture content rapidly and shrinks or expands with a change in atmospheric humidity to the extent of either showing an appreciable loosening or assuming a drum-head tightness when fastened along the edges. A finish of three coats of spar varnish very largely eliminates rapid change in moisture content.

WOVEN PLYWOOD.

Tests have been conducted upon plywood made up with basket-weave faces and corrugated core. The faces are woven out of splints of spruce veneer $1\frac{7}{32}$ inches wide and 0.017 inch thick, while the core is made of spruce $1\frac{7}{8}$ inches wide and 0.018 inch thick. The total thickness over all is almost 0.2 inch.

The following conclusion is drawn from the tests: The high rigidity at low loads, the high tearing strength, stability under varying humidities, and comparatively high toughness indicate that the woven plywood tested may be a very desirable material for construction in airplanes.

Data concerning glues for ply-wood will be found in the text under the general heading "Glues."

The following specification for waterproof plywood is based upon the strength tests just described and upon the glue tests presented farther on.

SPECIFICATION FOR WATER-RESISTANT VENEER PANELS OR PLYWOOD.

GENERAL.

1. General specifications for inspection of material, issued by the Bureau of Construction and Repair, in effect at date of opening of bids, shall form part of these specifications.

2. This specification covers the requirements for veneer panels for use in aircraft where a water-resistant ply-wood is specified.

MATERIALS.

3. The following species of wood may be used in plywood construction:

Basswood.	Mahogany (true and African).	Walnut.
Beech.	Maple (hard and soft.)	Western hemlock.
Birch.	Redwood.	White elm.
Cherry.	Spanish cedar.	White pine.
Fir (grand, noble, or silver).	Spruce.	Yellow poplar.

4. Other species of wood shall not be used without the written approval of the Bureau of Construction and Repair.

5. *Veneer.*—The veneer must be sound, clear, smooth, well-manufactured stock, of uniform thickness and free from injurious defects. Sap streaks and sound pin knots will not be considered defects. Discoloration will be allowed.

6. The veneer may be rotary cut, sliced, or sawed.

7. *Thickness.*—Unless otherwise specified, no single ply of veneer shall be thicker than $\frac{1}{12}$ inch. In three-ply stock the thickness of the core must be between 40 and 75 per cent of the total thickness of the plywood, except for panels one-sixteenth inch or less in thickness.

8. *Glue and cement.*—Any glue or cement may be used which will meet the tests specified in paragraphs 20 and 21.

MANUFACTURE.

9. *Grain.*—The grain in each ply shall run at right angles to the grain in the adjacent plies unless otherwise stated in the order.

10. *Manufacture.*—The plywood must have a core of soft or low-density wood and faces of hard or high-density wood unless otherwise specifically stated in the order. The core may be made of several plies, in which case the grain of the adjacent plies must be perpendicular. The plies must be securely glued together, after which the plywood must remain flat and free from blisters, wrinkles, lapping, checks, and other defects. Plywood manufactured with cold glue must remain in the press or retaining clamps not less than three hours.

11. *Joints.*—Plywood 10 inches wide or less shall have faces made of one-piece stock. In order to conserve the narrow widths of veneer, accurately made edge joints will be allowed in the faces and cores of wider stock, but the number of joints permitted in any ply shall not exceed the width of the panel, in inches, divided by eight. Edge joints are joints running parallel to the grain of the plies joined. All plywood built of jointed stock must be so constructed that all joints are staggered at least 1 inch.

12. In panels over 8 feet long scarf joints will be permitted; the smaller angle of the scarf shall have a slope of less than 1 in 25. Scarf joints in adjacent plies must be staggered. Scarf joints are joints in which the seam runs across the ply at right angles to the grain.

13. Butt joints will not be permitted.

14. In case the core or crossbanding is taped at joints only unsized perforated cloth tape or open-mesh unsized cloth tape applied with waterproof glue or cement shall be used.

15. *Moisture content.*—The finished plywood shall be dried to a moisture content of 9 to 11 per cent, with a tolerance of plus or minus 2 per cent, before it is shipped from the manufacturer's plant. The equalization of moisture shall be effected by kiln drying, followed by conditioning.

16. *Kiln drying.*—The panels must be piled and placed in dry kilns as soon as possible after being released from the press. The method of piling must be approved by the Bureau of Construction and Repair. After the stacking is completed the panels shall be properly weighted to prevent warping during the drying process. The best results in the kiln are obtained with a temperature of from 95° to 115° F. and a humidity ranging from 50 to 60 per cent, depending upon the thickness of plywood and number of plies. The circulation must be maintained at all times.

17. *Conditioning.*—All panels must be conditioned before fabrication or shipment. The conditioning shall be done indoors under temperature and humidity conditions existing in the factory for a period of not less than 24 hours for three-ply panels one-eighth inch thick and proportionately longer for thicker stock. The piling and weighting shall be the same as specified for dry-kiln stacks.

18. *Cutting.*—Cutting for length and width shall be full and true. The veneer shall be cut to the thickness desired in the finished plywood and any overallowance on this thickness for the sanding operation is very undesirable.

19. *Finish.*—In all cases the tape must be removed from the faces of the panel, and, unless otherwise specified in the order, the plywood shall be lightly sanded to a smooth finish free from defects.

TESTS.

20. *Submission of samples for test.*—The manufacturer shall submit to the Bureau of Construction and Repair for test 20 samples, each 1 foot square, of the plywood which he proposes to furnish to airplane manufacturers.

21. *Boiling or soaking test.*—The waterproof quality of the glue shall be tested either by boiling in water for a period of eight hours or by soaking in water at room temperature for a period of 10 days. After boiling or soaking the samples shall be dried at a temperature not exceeding 150° F. to a 10 per cent moisture content. The plies must not separate when the sample panels are subjected to this test.

22. *Shear test.*—The strength of the glue shall be tested in five test specimens cut from a sample panel. The form of the test specimen is shown in figure 43. The ends of the specimen shall be gripped in the jaws of a tension-testing machine and the load applied at a speed of less than one-half inch per minute. The glued surface must not fail at a load of less than 150 pounds per square inch.

23. *Approved list.*—Manufacturers whose plywood does not comply with these specifications will not be considered in awarding of contracts. The list of manufacturers whose product has satisfactorily passed the tests outlined in paragraphs 20 and 21 may be procured from the Bureau of Construction and Repair, Navy Department, Washington, D. C.

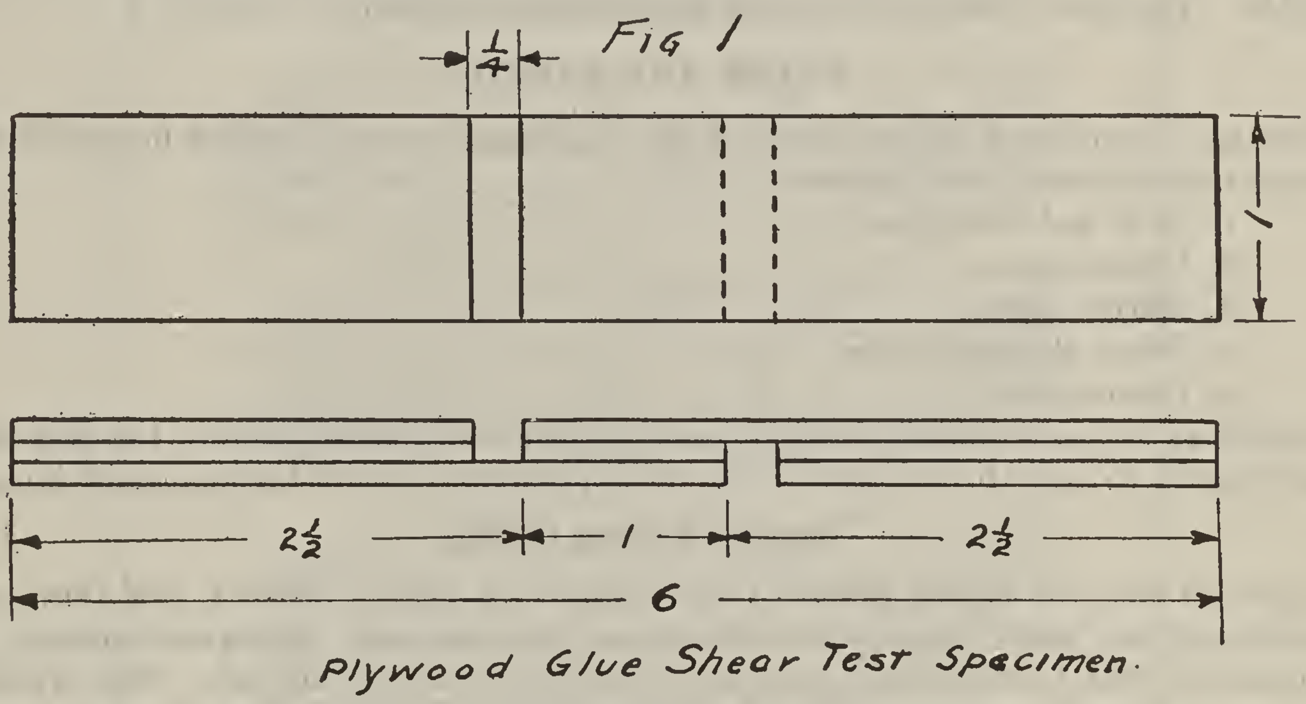


Fig. 43.—Plywood glue shear test specimen.

INSPECTION.

25. Unless otherwise stated, all veneer and plywood shall be inspected at the plywood manufacturer's plant.

26. The inspector shall make the tests specified in paragraphs 21 and 22 on at least one sample panel from each press for each eight-hours' run.

27. In case the plywood fails to meet the soaking and shear tests it shall be rejected. If the glue fails to meet one of these tests but passes the other, the test in which it fails must be repeated on not less than twice the original number of specimens selected taken from two or more panels. If the glue fails to pass the second test, the plywood represented by the samples must be rejected.

28. In case of consistent failure or lack of uniformity in product, the manufacturer will be required to submit a detailed written statement giving the following information:

(*a*) The composition of the glue and the correct practice in mixing it.

(*b*) The maximum time between mixing and applying the glue.

(*c*) The exact procedure in applying the glue and in pressing and curing the plywood and such other details as the Inspection Department may direct.

The inspector shall see that thereafter this schedule is observed.

29. The inspector shall have free access to all parts of the plants where the plywood is being manufactured and shall be afforded every reasonable facility for inspecting the materials used, the methods of manufacture, and the finished plywood.

PACKING AND SHIPPING.

30. Plywood which has passed inspection shall be packed in crates which will protect all edges and surfaces from injury during shipment.

ORDERING.

31. To facilitate the execution of contracts the order will state any special requirements which this material must meet. The order shall state the number of pieces, the width across the grain in inches, the length with the grain in inches, the thickness of the plywood and the individual plies, the number of plies, and the species of wood to be used for faces (to be marked "Faces"), for core (to be marked "Core"), and for cross-banding (to be marked "Crossband"). Sizes given shall be finished sizes and shall conform to commercial sizes when practicable. The order shall also bear the specification number.

GLUES AND GLUING.

There are a number of distinct kinds of glue commonly used in aircraft manufacture. The more important of these are as follows:

1. Hide and bone glues.
2. Liquid glues.
3. Marine glues.
4. Blood albumen glues.
5. Casein glues.

In addition to these there are many kinds of glue and cement used in the arts which are not well adapted to aircraft uses and which, consequently, need not be mentioned here.

HIDE AND BONE GLUES.

In general only the better grades of these glues are used in aircraft, and these are made from hides and are known simply as hide glues. Occasionally nonwater-resistant plywood panels made up with bone glue are used in unimportant parts of aircraft. The principal uses of hide glues in aircraft have been in laminated and spliced construction of various kinds, principally in propeller manufacture. Hide glue is still the standard propeller glue, though it has been replaced to an important extent in other laminated work.

In order to secure a very good grade of glue for propeller and similar work, suitable methods of testing were developed and certain specifications prepared. The Bureau of Aircraft Production regularly inspects lots of glue at the request of manufacturers, and glue passing the required tests is sealed and certified. It is then made available for purchase by aircraft manufacturers, who are thus assured of uniform glue of proper quality. The methods of test developed and used are given in detail in the following statement. The shearing test forms the basis for the certification of casein glue also.

TESTING OF HIDE GLUE.

Chemical analysis has been found practically useless as a means of testing glues because of the lack of knowledge of their chemical composition. Physical tests must, therefore, be relied upon. A considerable number of physical tests have been devised, some of which are important for one class of work and some for another. For judging the suitability of glue for high-grade joint work the tests considered most important are strength, adhesiveness, viscosity, jelly strength, odor, keeping qualities, grease, foam, and reaction to litmus. In the subsequent discussion of these tests their application to joint glue will be especially kept in mind.

Strength tests are made by gluing together two or more pieces of wood and noting the pressure or pull required to break them apart. Many different methods of making the test specimens and breaking them have been devised. These depend to a certain extent upon the character of work expected of the glue and the nature of the testing apparatus available. The simplest and most convenient strength test is to glue two blocks together, as shown in figures 44 and 45b, and shear them apart in a timber-testing machine (see fig. 45 a and c). It will

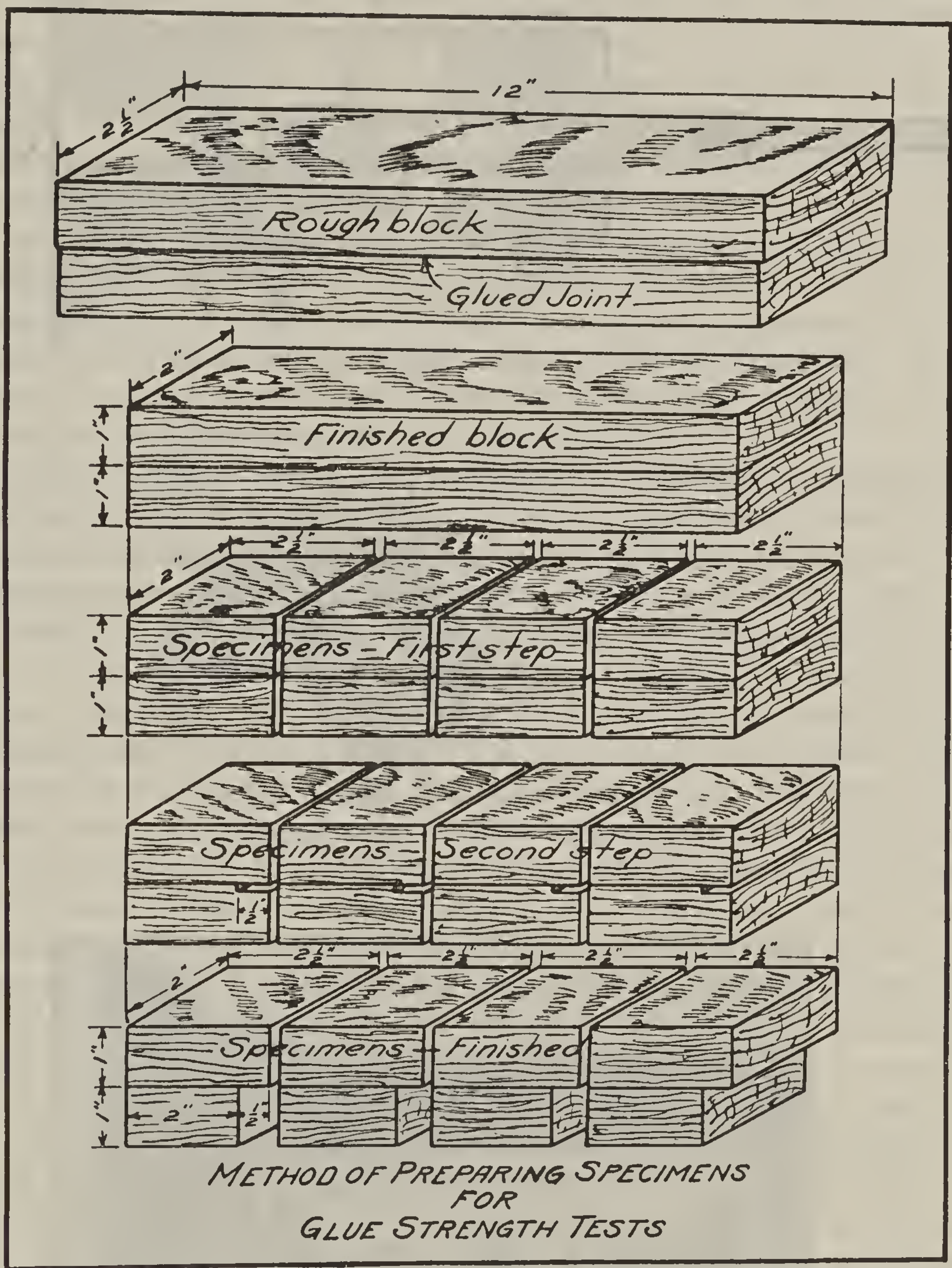


Fig. 44.—Method of preparing specimens for glue-strength tests.

usually be found that there is considerable difference in the values obtained for the individual specimens. The amount of difference, however, can be kept at a minimum by using care to see that the specimens are selected, prepared, and tested under as nearly the same conditions as possible. In making strength tests the selection of the wood is a very important factor. The species selected should be the one upon which it is proposed to use the glue or one fully as strong. Care should be taken also that the wood is above the average strength of the species, in order that there may be less opportunity for the wood to fail before the glue. If the wood is too weak, the full strength of the glue is not determined.

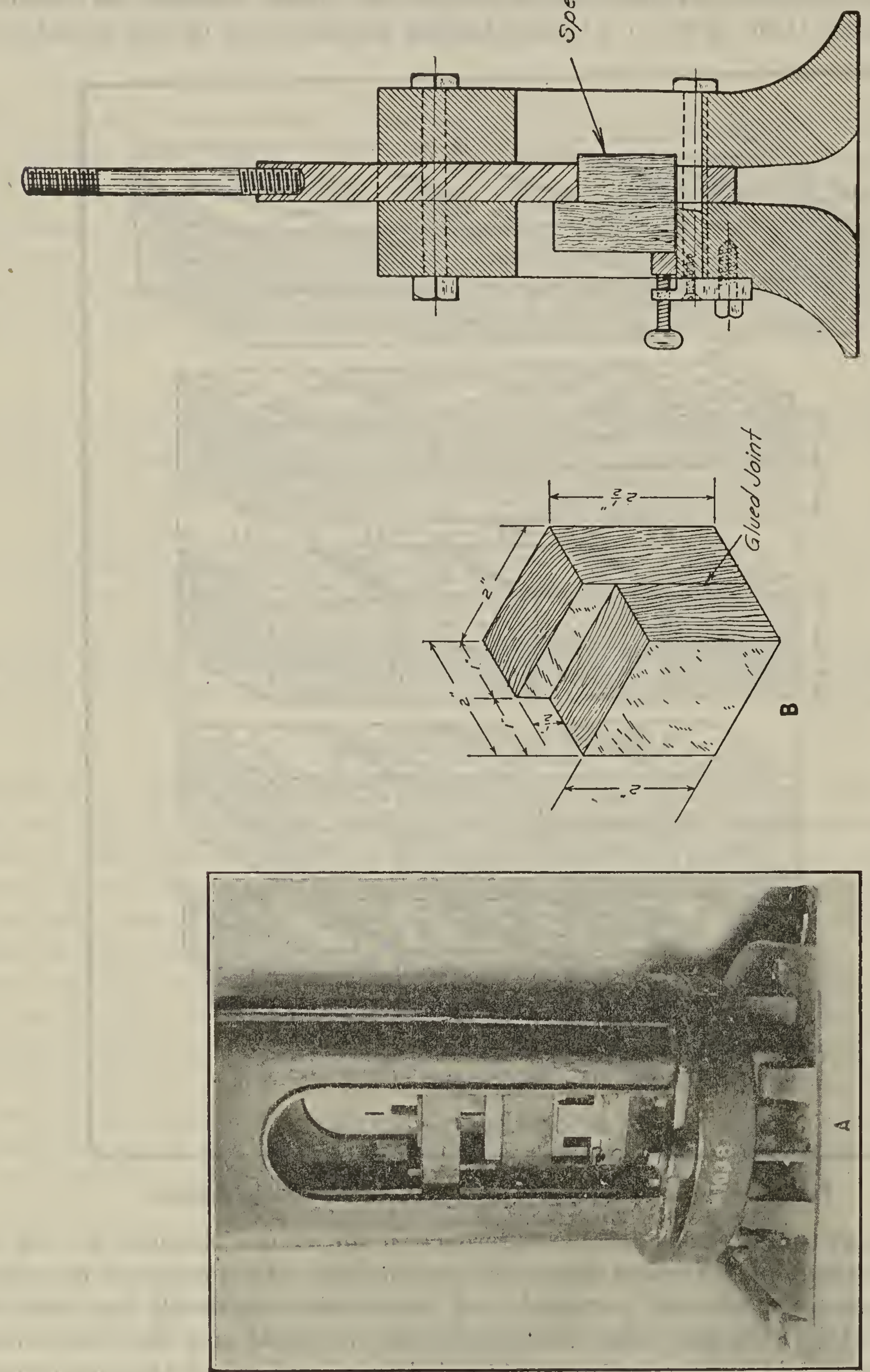


Fig. 45.—A. Testing machine with shearing tool in place. B. Finished specimen. C. Sectional view of shearing tool with test block in position.

No block should fail below 2,200 pounds per square inch, and the average shearing strength for a propeller glue should be at least 2,400 pounds per square inch.

The viscosity of a glue is determined by allowing a specified amount at a given temperature to flow through an orifice. The time required is a measure of the viscosity. The time required for water to flow through is taken as the standard. In general it is found that a glue with high viscosity is stronger than one with a low viscostiy and will absorb more water, although there are exceptions. Hide glues, as a rule, have higher viscosities than bone glues.

A number of different shaped viscosimeters have been devised. In the glue manufacturer's laboratory, where many tests must be made each day, an instrument must be used which will give results quickly. This can be done with a pipette cut off at one end or with a straight glass tube contracted at one end. These instruments are not always arranged so the temperature of the glue within them can be controlled, and for a number of other reasons they are not entirely accurate. Better control of temperature and greater accuracy can be had with the Engler viscosimeter. This is more complicated and more expensive than the glass tubes and also slower to operate, but it has the advantage, in addition to greater accuracy, of being an instrument which is in general use for testing many kinds of materials. The values obtained by its use are readily understood by laboratory men and can be readily checked. The instrument can be purchased standardized and ready for use.

The term "jelly strength" refers to the firmness or strength of the jelly formed by a glue solution of specified strength upon cooling. Strong glues usually have high jelly strength. There is no standard instrument for determining jelly strength and no standard unit for expessing it. In some laboratories the pressure required to break the surface of the jelly is measured. In others the depth to which a weight of special shape will sink is observed. Sometimes the jelly is cast in a conical shape, and the weight required to press the point of the cone a certain distance is taken. More common, however, is the finger test, in which the relative strength of two or more jellies is compared by pressing the jelly witn the fingers. In making this test with any apparatus it is important that the conditions be very carefully controlled in order that comparative results may be obtained. The temperature of the jelly when tested is particularly important, as the relative strength of a number of jellies is not the same at different temperatures. In other words, the jelly strength of the different glues is not affected to the same extent by changes in temperature. The ideal condition is to cool and test the jellies in a room constantly maintained at the proper temperature. This is seldom practicable, however, and the jellies must be cooled in a refrigerator and tested in a warmer room. When this is done it is important that the test be made as quickly as possible after removing the jelly from the refrigerator, so that the temperature will be practically the same as it was in the refrigerator. The strength of the glue solution must always be the same once a standard is adopted. For high-strength glues weaker solutions can be used than for low-strength glues.

The odor of a glue is determined by smelling a hot solution and gives some indication of its source or its condition. Glue which has an offensive odor is not considered of the highest grade. The bad odor may be due to the fact that partly decomposed stock was used or that the glue itself is decaying. For high-grade work it is usually specified that the glue be sweet; that is, it must not have an offensive odor. The odor of different glues varies considerably, and it is difficult or impossible to express the different "shades." It is usually not difficult, however, to determine whether or not the odor is clean, or, as it is commonly called, sweet. The temperature and strength of solution are not usually specified.

The keeping quality of a glue is determined by allowing the jelly left from the jelly-strength test to stand in the laboratory at room temperature for a number of days. The odor and con-

dition of the glue are noted at intervals. Glues with good keeping qualities will stand several days without developing an offensive odor or showing any appearance of decomposition.

For joint work a small amount of grease in glue is not a serious objection. Too much grease, however, is objectionable, as grease has no adhesive properties. The grease can be determined by chemical means, if desired, but this is not necessary unless the exact amount of grease must be determined. The common method of testing for grease is to mix a little dye with the glue solution and paint it upon a piece of unsized white paper. If grease is present, the painted streak will have a mottled or spotted appearance. If there is no grease present, the streak will have a uniform appearance.

Glue which foams badly is objectionable because air bubbles are apt to get into the joint and thus reduce the area over which the glue is in contact with both faces. Foamy glue is especially undesirable for use in gluing machines, as in them the glue is agitated much more than when it is used by hand, and the danger of incorporating air bubbles is greater. The amount of foam is tested by beating the glue solution for a specified time with an egg beater or similar instrument and then noting the height to which the foam rises and the quickness with which it subsides. Different laboratories do not make the test in exactly the same way, but in any laboratory after a method is once adopted it should be strictly adhered to thereafter. It is common to determine the foam on the solution used in the viscosity test.

By its reaction to litmus a glue shows whether it is acid, alkaline, or neutral. The test is made by dipping strips of red and blue litmus paper in the glue solution remaining after the viscosity test or some other test and noting the color change. An acid glue turns blue litmus red, an alkaline glue turns red litmus blue, and a neutral glue will not change the color of either red or blue litmus. A glue containing a slight amount of acid is slightly preferable to one which is neutral or alkaline, because it is not quite so favorable a medium for the growth of the organisms which cause the decay of glue.

From the above description of the various glue tests it is apparent that, for the most part, they give comparative rather than absolute results. It is rather difficult to compare the results of tests made by one laboratory with those of another, as the strength of solution, temperature, and manipulation are often different. For this reason the most satisfactory method of purchasing glues is to specify that they must be equal to a standard sample which is furnished the bidder to test in any way he sees fit. The bidder should also be informed as to the methods the purchaser proposes to use in testing a glue submitted to him as equal to the standard sample.

PRECAUTIONS IN USING HIDE GLUE.

In using hide glue there are a number of precautions that must be observed to obtain satisfactory results. If improperly used, a very high-grade glue may give poor joints. It is important, first, to find out the right proportion of glue and water to get the best results. This is largely a matter of experience, but it can also be determined by strength tests. When the right proportions are decided upon, they should be strictly adhered to thereafter, and the glue and water should be weighed out when making up a new batch of glue rather than measured or guessed at. Clean cold water should be put on the glue, which should be allowed to stand in a cool place until it is thoroughly water soaked and softened. This may take only an hour or it may take all night, depending upon the size of the glue particles. When the glue is soft, it should be melted over a water bath and the temperature not allowed to go higher than about 150° F. High temperatures and long-continued heating reduce the strength of the glue solution and are to be avoided. The glue pot should be kept covered as much as possible in order to prevent the formation of a skin or scum over the surface of the glue.

The room in which the glue is used should be as warm as possible without causing too much discomfort to the workmen, and it should be free from drafts. In a cold, drafty room the glue cools too quickly and is apt to set before the joint has been put into the clamps. This results in weak joints. It is also considered good practice to warm the wood before applying the glue. Wood should never be glued when it is cold, and of course only thoroughly seasoned wood should be used. Since high-strength animal glues set so quickly on cooling, they should be applied and the joints clamped as quickly as consistent with good workmanship.

In clamping glued joints the pressure should be evenly distributed over the joint, so that the faces will be in contact at all points. The amount of pressure which will give the best results is a question which has never been definitely settled. One experimenter found that a pressure of about 30 pounds per square inch gave better results on end joints than higher or lower pressures. Apparently no tests have yet been made to show the best pressure to use on edge or flat grain joints. In gluing veneers it is necessary to use high pressure in order to flatten out the irregularities of the laminations. Pressures as high as 150 or 200 pounds per square inch are sometimes used.

Strict cleanliness of glue pots and apparatus and of the floors and tables of the glue room should be observed. Old glue soon becomes foul and affords a breeding place for the bacteria which decompose glue. The fresh glue is therefore in constant danger of becoming contaminated. Glue pots should be washed after every day's run in hot weather and two or three times a week in cooler weather. Only enough glue for a day's run should be mixed at a time, so that mixed glue will not have to be held over from one day to another. If these sanitary precautions are not observed, poor joints are apt to be the result.

LIQUID GLUES.

Liquid glues, frequently known as fish glues, have been used to quite an extent for the smaller work such as gluing cap strips, tape, blocks, moldings, etc. They are being replaced gradually by casein glues, which have the advantage of water resistance. In general liquid glues are not as strong as certified hide glue, although the shearing strength of several which have been tested has been as high as 2,400 pounds per square inch.

MARINE GLUES.

These glues are used mainly to apply muslin between the inner and outer skins of floats and flying boat hulls. They are required to be of a sticky, viscous nature and relatively nondrying and elastic. They are usually composed of pine tar, rosin, manila resin, and alcohol. On account of their nondrying nature, these glues have comparatively low strength. They are readily soluble in gasoline, and it is necessary, therefore, to make provision to prevent gasoline from getting into the bilge water. In general, marine glues are not used to make joints in wood construction where high strength is required.

BLOOD ALBUMEN GLUES.

These glues, which are made from blood albumen secured from packing houses, are the strongest and most water resistant of all so-called "waterproof glues" in common use to-day. In general, it is necessary to use heat (about 225° F.) to set them, and consequently their usefulness is limited largely to plywood and similar thin material, although it is possible to glue thicker material in cases where the proper heat can be applied successfully. Practically all plywood glued with blood glues is glued between steam-heated plates, which furnish a convenient source of heat.

Properly manufactured blood albumen plywood will pass all the tests prescribed in the plywood specification without difficulty. Not only does the shearing strength average far above that required, but the resistance to boiling and soaking is generally much greater than the specification requires. Further, the residual strength of the glue after boiling and soaking is, in general, decidedly superior to that of casein glues.

A method has recently been developed for the gluing of very thin plywood, in which fine tissue paper is impregnated with blood albumen glue and then dried. This tissue is then used just as ordinary mending tissue. A sheet is placed between the layers of veneer to be glued and the whole put under pressure between steam-heated plates. Since the process is a dry one, the troubles due to swelling and warping are eliminated.

In general, it is anticipated that the use of blood albumen glues will be confined to manufacturers of plywood for some time to come and that the only contact which the aircraft manufacturer will have with it will be in the plywood which he purchases.

CASEIN GLUES.

The major ingredient of these glues is casein, a product secured from the souring of milk. Until a year ago casein glues were hardly known in this country, but they have been developed commercially by several concerns, and their use in aircraft has increased rapidly. They have the advantage that they may be used quite cold and that no heat is used either in mixing or in setting them. Further, they set up quickly but have the disadvantage of taking a comparatively long time to develop their maximum strength.

Casein glue is widely used in making water-resistant plywood and its use in laminated construction (except propellers) is steadily increasing. It is also being used in places where formerly fish glues were mostly used.

The best grades of casein glue are fully as strong as certified hide glue in shear, and their resistance to high humidities and to soaking is much greater. Tests now under way indicate that the shock resistance of casein glues is as great as that of certified hide glue. The technical use of casein glue is very simple, but it is necessary to follow instructions carefully in order to secure best results. The instructions which follow represent the best practice and are based upon experience both in laboratory and in the shop.

INSTRUCTIONS FOR USE.

Equipment.—In using waterproof casein glues the mixers used ordinarily for animal glue and vegetable glue are generally not very successful, as a more rapid and thorough stirring than these mixers give is usually necessary. It is possible that some types of ordinary glue mixers can be speeded up enough to give good results with casein glues, but they have additional disadvantages in being rather difficult to keep clean. The most successful mixer so far found for these glues is the power cake mixer, such as is used by bakers, or machines constructed on a similar plan. These machines have several speeds and mix the glue in a detachable kettle which is easily cleaned. They can also mix relatively small quantities, so that no batch of glue needs to stand very long before being used up. Copper, brass, or aluminum vessels should not be used for mixing casein glues, as the alkali in the glues attacks these metals. It is advisable also to equip the glue pot with a metal hood fitted with a feed hopper in order to prevent spattering outside of the glue pot during the course of mixing.

Preparation of glue.—It is advisable, in all cases, to thoroughly mix the contents of a freshly opened barrel of prepared glue, and preferably several barrels should be mixed at once before any of the dry powder is withdrawn for use, in order to counteract the segregation of ingredients of varying specific gravities which may have occurred during shipment from the factory to the point of consumption. This mixing may be accomplished by transferring the

contents of the barrels to a box of suitable size in which the dry glue is turned over a sufficient number of times and thoroughly mixed with a clean shovel.

It is necessary to caution against the practice observed in some plants of sifting the powdered glue and discarding from it the coarse matter which remains upon the screen. This may remove from the glue an essential ingredient and thus defeat the purpose for which the glue is intended.

Proportions of dry glue and water.—The proportion of water to mix with the dry glue should be as directed by the glue manufacturer. It is to be borne in mind, however, that fixed proportions, satisfactory for each and every barrel of glue received, can not be specified because of a slight lack of uniformity which may exist in the product. Hence, only average proportions can be stipulated by the manufacturer, and the operator, in order to obtain satisfactory consistencies, may find it necessary at times to vary from the average proportions specified. It has been found in some cases that using exactly the same proportions of glue and water, the glue from one barrel may be thinner than that from another. It is hoped that this difficulty will be overcome before long by improved manufacturing methods, but until it is much will have to depend upon the judgment of the operator. It should also be remembered that some classes of work require thicker glue than others.

Mixing the glue.—The correct quantity of water is placed in the glue pot and the mixing blade is brought into action at proper speed. A high speed is necessary at first, especially if the glue is not added to the water very slowly, in order to avoid the formation of lumps in the glue. There is a considerable range of speed, however, which will give satisfactory results. In some cases a speed of 140 revolutions per minute of the shaft which carries the mixing blade (about 350 revolutions per minute of the blade itself) is used satisfactorily. By adding the glue carefully, however, a speed as low as 80 revolutions per minute of the vertical shaft (180 revolutions per minute of the blade) can be successfully used. The powdered glue is now slowly introduced through the feed hopper and the agitation is allowed to continue for about five minutes and then stopped.

The sides of the glue pot should now be scraped in order to direct any of the spattered material into the mixture, whereupon the blade is again brought into action at reduced speed (60 to 90 revolutions per minute) for a period of at least ten minutes. The object of reducing the speed after the first stage of mixing is to prevent the incorporation of an excess of air. At the end of this stirring period the glue is ready for use, provided all the fine casein particles are dissolved and no appreciable amount of air has been whipped in. If the glue still contains fine particles of undissolved casein and has the appearance of "cream of wheat" mush, however, the mixture should be continued. It was formerly considered necessary to allow the glue to stand without stirring for a short period before using it. The object of this was to allow all the casein to dissolve. It has now been found, however, that it is better practice to accomplish this solution by continued mixing than by standing. If, however, it is found that air bubbles have been whipped into the glue during mixing, it is desirable to let it stand awhile so the air can separate.

In mixing casein glues which may require the addition of different ingredients singly the above practice should be varied from to conform with the directions of the manufacturer.

Consistency of glue.—It may be found that the proportions used do not always give exactly the same consistency. So long as the glue is neither too thick nor too thin to spread well, however, slight differences in consistency between individual batches or shipments of glue need not be considered serious. Good results may be expected if the glue spreads properly. Other things being equal, thick mixtures develop higher strength than thin mixtures, and when great strength is desired it is desirable to use the thickest mixtures practicable.

If in mixing up a batch of glue from a new barrel or shipment of some kinds of glue it is found that the proper consistency is not obtained, it is possible to alter it if attended to immediately and before the glue has been removed from the mixing pot. This should not be attempted on important work unless the operator fully understands his glue, and it should be entirely avoided if possible.

If the glue mixture obtained is seen, before it is taken from the mixing pot, to be too thick to spread properly, it can be thinned by adding an extra part or two of water, as may be required, and stirring at slow speed until the water is thoroughly incorporated. This holds for any casein glue. Under no circumstances, however, should water be added to glue which has thickened on standing or after being used awhile.

If the glue mixture is found, before removing from the mixing pot, to be too thin, it may be thickened by carefully adding a proper amount of dry glue with continued stirring. This is practicable only for glue in which all the ingredients are mixed together dry, and is not suitable for glues in which the various ingredients are added separately. The stirring should then be continued long enough to dissolve all the casein of the added glue. Another method which might be used is to mix a thicker batch of glue and then mix the two batches together. It is far preferable to avoid using either method, and with proper care it should seldom be found necessary.

Application and use of glue.—The glue in any batch should be used up completely before it begins to thicken materially. The length of time during which the mixed glue can be successfully used may vary with different shipments. The operator must judge whether or not the glue is fit to use at any time by its consistency. Tests have shown that good results may be expected from a normal glue at any time during its working life up to the time when it becomes too thick to spread properly.

In spreading the glue it is important that enough be applied to coat all the surface of both faces of the joint. An appreciable amount of glue should squeeze out of the joints when pressure is applied. As little time as possible should elapse between the spreading of the glue and the pressing. The exact time which can safely elapse will vary with the kind of wood being used, the consistency of the glue, the amount of glue applied, the temperature, and other factors. In making veneer panels it is considered best practice to get the stack under pressure within ten minutes or less from the time the first ply is spread.

The minimum time the joints must be left under pressure is not known. It is considered safest and best practice, however, to leave the joints in the press or in retaining clamps for at least three hours. After the glued material is taken from the press it should be dried either artificially or naturally to remove the moisture added by the glue. It is best also to allow the material to stand a week or two to develop the full strength and water resistance of the glue. The panels should, of course, be piled properly during the drying period to prevent warping.

The above discussion is applicable in general to casein glues, whether of the prepared type, such as Certus, Napco, Casco, or Perkins waterproof glue, or of the type which is mixed by the user directly from the raw materials.

The following points should be kept in mind in preparing and using casein glues:

(1) Thoroughly mix each barrel of glue before using.
(2) Weigh the glue and water; do not measure it.
(3) Avoid lumpy mixtures.
(4) Avoid mixtures which are too thick or too thin.
(5) Mix until all the fine particles dissolve and a smooth mixture is obtained.
(6) Do not use glue after it becomes too thick to spread properly.
(7) Do not attempt to thin or thicken glue after it leaves the mixer.

DIRECTIONS FOR MIXING CERTUS GLUE.

In general use about 10 parts of glue and 17 to 20 parts of water. Both water and glue should be weighed, not measured. With the water in the mixing can, start the mixing blade at high speed (80 to 140 revolutions per minute of the vertical shaft is about right) and add the dry glue rather slowly. Continue this rapid stirring for about 3 to 5 minutes after the last dry glue is added; then stop the mixer, scrape down the sides of the can, and start mixing at slow speed (40 to 60 revolutions per minute of the vertical shaft is about right). After 10 to 15 minutes at slow speed the glue should be ready for use. If it has a granular appearance at the end of this time, however, the casein is not all dissolved, and mixing should be continued long enough to get casein particles into solution. The glue is then ready to use.

DIRECTIONS FOR MIXING NAPCO GLUE.

In general use about 10 parts of glue and 17 to 20 parts of water. Both water and glue should be weighed, not measured. With the water in the mixing can, start the mixing blade at high speed (80 to 140 revolutions per minute of the vertical shaft is about right) and add the dry glue rather slowly. Continue this rapid stirring for about 3 to 5 minutes after the last dry glue is added, then stop the mixer, scrape down the sides of the can, and start mixing at slow speed (40 to 60 revolutions per minute of the vertical shaft is about right). After about 30 minutes at slow speed the glue should be ready for use. If it has a granular appearance at the end of this time, however, the casein is not all dissolved, and mixing should be continued long enough to get the casein particles into solution. The glue is then ready to use.

DIRECTIONS FOR MIXING CASCO GLUE.

Before starting any mixing weigh out all ingredients, using the following proportions:

$$A\begin{cases}\text{Water, } 22\tfrac{1}{2} \text{ parts.}\\ \text{Prepared Casco casein, 10 parts.}\end{cases}$$

$$B\begin{cases}\text{Water, 1 part.}\\ \text{Caustic soda, } \tfrac{1}{2} \text{ part.}\end{cases}$$

$$C\begin{cases}\text{Water, 5 parts.}\\ \text{Hydrated lime, 5 parts.}\end{cases}$$

With the water of A in the mixer and paddle operating at an intermediate speed (in the neighborhood of 60 to 90 revolutions per minute of the vertical shaft of a cake and dough mixer) slowly add the casein and continue stirring till the mass is free from lumps. This should require about 3 or 4 minutes.

Now slowly add the one-half part of caustic soda which has been previously completely dissolved in the 1 part of water, and continue stirring for about 3 minutes.

Next add the 5 parts of hydrated lime which has previously been worked into a smooth paste with the 5 parts of water, and continue stirring until a smooth mixture free from lumps and undissolved particles of casein is obtained. This should require about 15 minutes, possibly a little longer. The glue is now ready for use. If it is found that any appreciable quantity of air has been incorporated into the glue by the stirring, the glue should be allowed to stand 10 to 20 minutes before using to allow the air to escape.

Glue mixed according to the above procedure is ordinarily considered satisfactory for gluing veneer one-twelfth inch thick or thinner. If the glue appears too thin, however, it can be made thicker by using less water, as suggested below. For joint work or thicker veneer also a somewhat thicker consistency is desirable. This can be obtained by using 17 to 20 parts of water under A instead of $22\frac{1}{2}$ parts.

DIRECTIONS FOR MIXING PERKINS WATERPROOF CASEIN GLUE.

(As recommended by the manufacturer September, 1918.)

When the paddle itself is running about 400 revolutions per minute, the following method is highly satisfactory for making up "P. W. G." into finished glue:

Dissolve 1 pound of 76 per cent caustic soda in 30 pounds of water contained in the large bowl. Add 14 pounds of "P. W. G." slowly to the caustic solution with thorough and brisk agitation. Continue agitation for about 5 minutes. Allow the glue to stand 20 to 30 minutes after mixing before using.

When the speed of the paddle itself is less than 400 revolutions per minute the following method will give a smooth, fine flowing batch:

Add 14 pounds of "P. W. G." to 27 pounds of water. Agitate to smooth consistency. Continue agitation and add in small portions a solution made by dissolving 1 pound of caustic soda in 3 pounds of water. Continue agitation for about 5 minutes after ingredients are all in. Allow to stand 20 or 30 minutes after mixing before using.

Neither casein nor blood albumen glues seem to be affected by gasoline in the slightest degree. A number of panels made up by representative manufacturers were soaked for a long period (several months) in gasoline without any sign of deterioration. Similar panels were also soaked for a like period in gas engine oil (Polarine) without any apparent deterioration. These tests indicate that both blood albumen and casein plywoods can be used around the engine without fear of damage by gasoline and oil.

Frequently it becomes desirable to fill, shellac, or varnish parts which are later to be glued. Tests made to determine the strength of joints made on wood treated in this manner show that they are very weak and absolutely unreliable. No joints in aircraft work should be made except with the bare wood.

AIRCRAFT PARTS.

On account of the impossibility of computing, with any degree of accuracy, the strength of many aircraft parts and assemblies, it has been found necessary to supplement the designs and calculations with actual test to destruction. The tests have frequently shown unexpected weak points, which have been strengthened and the parts retested. Through development of this character some very remarkable results have been achieved, and the way has been opened for similar work along allied lines.

LAMINATED CONSTRUCTION.

One of the first problems to come up in this connection was a study of laminated wood construction. Opinion concerning the merits of this type of construction have been divided for a long time, and designers have allowed their fancy free reign in devising widely varying styles of built-up members. Until about a year ago designers were allowed to use either solid or built-up construction, in accordance with their individual needs or desires, but during the present year there has been a very decided trend toward official insistence upon laminated construction in preference to solid, especially in the case of wing spars. There are several reasons back of this trend, not the least important of which is the increasing difficulty of securing large sizes in the desired grades. In the case of propellers lamination has been practically universal for many years.

While lamination undoubtedly does promote the use of smaller and shorter material, with the consequent better utilization of lumber and does insure the elimination of large hidden defects, it requires the exercise of a great deal of care to insure satisfactory results. The principal difficulties encountered lie in the warping and twisting of the finished part. The relations

existing between shrinkage and moisture, density, and direction of grain have already been discussed in detail. Let it suffice to say that unequal shrinkage, with consequent twisting or warping, will result in a laminated structure if the various laminations differ materially from each other in any of the three factors mentioned, namely, moisture, density, and direction of grain.

Propellers probably need as much care in their manufacture as any aircraft parts in order to insure permanence of pitch, balance, etc. The following rules for the selection of wood for laminated construction have been prepared especially for propeller manufacture, though they apply in general to all laminated construction:

(1) All material should be quarter-sawed if possible.
(2) Quarter and flat-sawed laminæ should not be used in the same propeller.
(3) All laminæ should be brought to the same moisture content before gluing up.
(4) All laminæ in the same propeller should have approximately the same specific gravity.
(5) All laminæ in the same propeller should be of the same species.

Dry wood when exposed to very humid air absorbs moisture and swells. Wood dried in a normally dry atmosphere till its moisture content becomes practically constant loses moisture, and shrinks when exposed to extremely dry conditions. Two pieces of wood when exposed continuously to the same environment will eventually come to practically the same moisture content, irrespective of their relative moisture contents when first exposed to this environment.

Individual pieces of wood, even those of the same species, vary greatly in their rate of drying. Quarter-sawed pieces have a different drying rate from plain-sawed pieces. Dense pieces dry more slowly than those which are less dense.

Suppose that a flat-sawed board is glued between two quarter-sawed boards, all three having the same moisture content, say, 15 per cent, when glued up; or, suppose, that under similar conditions a very dense piece is glued between two pieces which are less dense; or, suppose that a board containing 15 per cent moisture is glued between two others, each containing 10 per cent but all three being of the same density and cut in the same manner. Then suppose the finished product to be dried to, say, 8 per cent moisture. Every piece will shrink, but in each instance the center piece will tend to shrink more than the outside ones. The glued joint will be under a shearing stress, since the center piece has a tendency to move with respect to those on the outside. Under this condition the glued joint may give way entirely, it may partially hold, or it may hold perfectly. In either of the latter cases the center piece will be under stress in tension across the grain, and consequently will have a tendency to split. This tendency may become localized and result in visible splitting or it may remain distributed and cause a lessening of the cohesion between the wood fibers, but without visible effect.

If a combination of these three cases occurs, it may be much more serious in its effect than any one alone. For instance, suppose that in a propeller alternate laminations are of flat-sawed, dense boards, glued at a relatively high moisture content, while the others are quarter-sawed, less dense, and at a much lower moisture when glued. The tendency of the flat-sawed laminations to shrink will be very much greater than that of the others, with the result that internal stresses of considerable magnitude will be set up.

It is not difficult to see how these internal stresses may combine with the stresses from external causes and with the continual vibration to produce failure under external loads which are considerably smaller than the propeller would safely resist if manufactured with proper care.

In the case of laminated struts and beams the laminations should be matched as to direction of annual rings, as they appear on the end section, to balance shrinkage as much as possible.

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Quarter-sawed and flat-sawed material should never be used in the same member. Neither should either quartered or flat stock be used with stock cut at intermediate angles. In laminating together pieces cut with the annual rings at an angle of about 45 degrees with the faces the rings in the adjacent laminations should be approximately perpendicular to each other instead of approximately parallel to each other.

WING BEAMS.

In order to determine the general principles underlying the design of built-up wing beams, to develop the best forms from the standpoints of efficiency, utilization of low-grade stock, and ease of manufacture, and to study problems connected with manufacture, a series of 300 beams of various types and designs were built and tested. These types included only those which gave promise of strength efficiency combined with utilization of smaller material than that needed for the manufacture of solid beams, since the problem at the time was primarily one of shortage of material. The types selected besides the solid ones used for comparison are shown in figure 46.

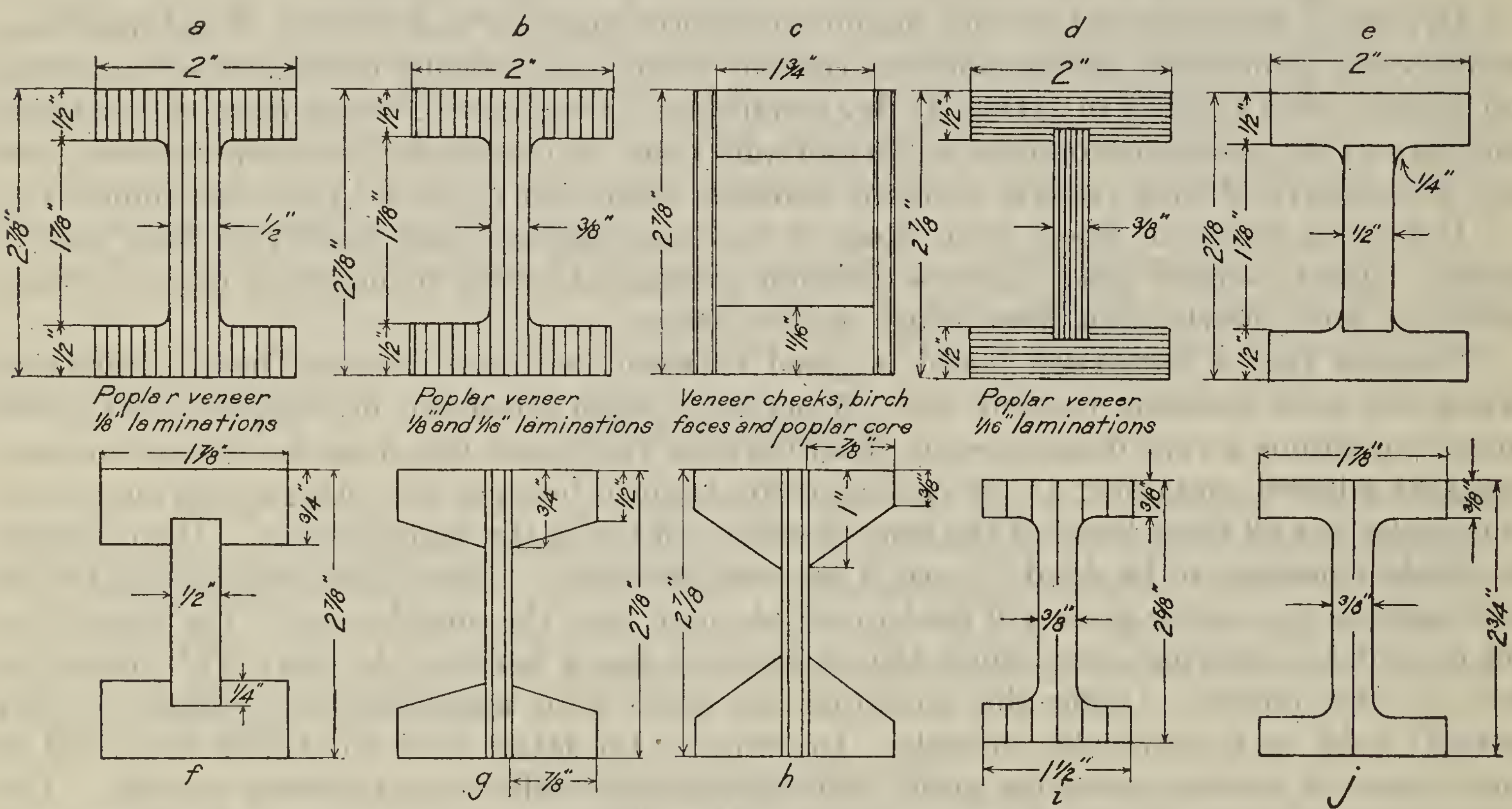


Fig. 46.—Cross sections of built-up test beams.

While it is impossible at the present time to present detailed analyses of these tests, the general conclusions drawn from them are given in the following statements:

The tests were divided into various series for ease in reference, each series representing different conditions from the others. The conclusions from each series are first given, with the general conclusions at the end.

RESULTS OF VARIOUS BEAM TESTS.

Series 1 and 12 (fig. 46e and f): These consisted of one-piece spruce beams of acceptable material compared with three-piece beams of similar matched material. The results compared favorably, although with the built-up beam without filleted joints (Fig. 46f), the work to the maximum load was approximately two-thirds of that of the single-piece beam. On the other hand, the work to maximum work in the other series (fig. 46e) was 20 per cent higher than for the single-piece beams. Consideration of the results as a whole indicate that this type of beam, properly glued, will compare favorably with the single-piece construction.

Series 2 and 13 (fig. 46i): This series included single-piece spruce beams made from rejected material compared with laminated spruce beams made from similar matched material. The laminated material gave 5 to 10 per cent lower values in modulus of rupture and 5 to 10 per cent greater values in work to maximum load. The results show that not only will the glue hold satisfactorily but that higher values would not be secured by laminating defective material than by using it in solid form.

Series 3 and 10 (fig. 46b): Series 3 is made from one-eighth-inch poplar with the grain of all plies longitudinal compared to similar material and construction with the grain of the center ply vertical.

Series 10 consists of beams of one-sixteenth-inch poplar laminations with vertical joints.

Three types were made up as follows: (*a*) The grain of the center ply vertical; the grain of all other plies horizontal. (*b*) The grain of all plies having a slope of one in five from the horizontal, the slope in adjacent plies being in opposite directions. (*c*) The grain of the six center plies having a slope of one in five from the horizontal, the slope in adjacent plies being in opposite directions; the grain of all other plies (namely the flange plies) being horizontal.

The tests showed (1) a 5 to 10 per cent reduction in the mechanical properties where the grain of the center ply was vertical, with no reduction made in the thickness of the web due to using this form of construction; (2) a reduction of approximately 20 per cent in total load and stiffness where a slope of one in five was used in alternate directions in adjacent laminations throughout the whole beam; (3) a reduction midway between the foregoing where a slope of one in five in alternate directions was used only in the web.

The conclusions to be drawn from this series are that if cross-grained material must be used, better results would be secured by laminating and placing the grain of adjacent laminations in opposite directions than to use solid beams of similar material, but that it would not be possible to secure a strength equivalent to beams of satisfactory grain throughout.

Series 4 (fig. 46g): A plywood web with Douglas fir flanges was used in this series, and included beams with the grain in the outside plies of the web longitudinal, vertical, and at 45 degrees. Hide glue was used in making the beams, and failures of the glued joints developed in the tests presumably due to faulty control in the application of the glue. These tests are being repeated, using casein glue.

Series 5 and 6 (figs. 46g and h): These series included spruce flanges with plywood webs. The face plies were one-thirty-second inch with vertical grain, while the thickness of the core was varied from one-eighth to one-sixteenth inch. The results indicate the desirability of making a web of this construction somewhat thicker than required for shear stresses only.

Series 7 (fig. 46c): An acceptable grade of spruce with plywood sides was used in these tests. Four thicknesses of plywood were used, as follows:

Outside plies $\frac{1}{32}$ inch, core $\frac{1}{8}$ inch.
Outside plies $\frac{1}{24}$ inch, core $\frac{1}{8}$ inch.
Outside plies $\frac{1}{32}$ inch, core $\frac{1}{16}$ inch.
Outside plies $\frac{1}{100}$ inch, core $\frac{1}{64}$ inch.

This type of beam gave very satisfactory results but the very thin plywood proved entirely inadequate. The results indicate that plywood with a one-sixteenth-inch core and one-thirty-second-inch faces would be suficient and that possibly a lighter construction would prove satisfactory.

Series 18 (fig. 46d): This series included beams made up of one-sixteenth-inch poplar veneer with the center ply of the web vertical. The results were satisfactory and showed that the glue held sufficiently to develop the strength of the section. This type of beam, however, would probably be increased in weight about 10 per cent above that of a solid beam of similar material due to the large quantity of glue which would be required.

Series 11 and 19 (fig. 46j): This series used white pine, with one-half of each beam of quarter-sawed and the other half of plain-sawed material and with moisture content 5 per cent higher in one-half of the beam than in the other. It is planned to subject different beams from this series to varying conditions of humidity in order to determine the effect of such conditions where the grain of the two faces of the beam are of a different character and in different directions. The greater part of this series has not yet been run, but the variations in results not due to the gluing indicate that greater defects can not be allowed in either piece than are now allowed in solid beams.

GENERAL CONCLUSIONS.

In general, practically all types of beams so far tested have given values commensurate with what might be expected of the section under test. In other words, the tests have shown that waterproof glue properly applied enables the full value of the section to be developed.

Since the success of the laminated type of construction is primarily dependent upon the efficiency of the glue, it is of the utmost importance that means be provided to insure the satisfactory supervision of the technique of gluing.

The types of beam illustrated in figure 46e and f and in figure 46c seems to offer the most immediate opportunity for effectively increasing production from the class of material now on hand and being received by the airplane manufacturers. Since in the types indicated in figure 46e and f spiral grain material can be used in the webs, these types would have the particular advantage of permitting utilization of material now rejected. The tests thus far made indicate that these beams properly made are no more variable in their strength properties than solid beams.

All of the beams of the foregoing series were made under laboratory conditions. In order to determine just what might be expected under factory conditions, several hundred of the types shown in figure 46c and e were ordered from various aircraft manufacturers and tested. The results of these tests, while not yet completely analyzed, show that, with proper supervision, it is possible for the average aircraft manufacturer to produce satisfactory built-up beams. They also show, however, that the need for thorough, intelligent supervision is imperative.

In addition to these series, numerous miscellaneous types of beams have been tested. Several of these types were similar to the types which have become more or less standard, while others may be considered freak designs. So far none of these freak designs have shown up satisfactorily. Several of the designs had some form of plywood in the flanges. In no instance have beams of this type proven as strong as beams with solid flanges or flanges in which all the grain was parallel to the longitudinal axis. Figure 47 shows various types of wing beam construction which have been used in machines or approved for use.

BEAM SPLICES.

Until the present year the matter of beam splices had not received a great deal of attention. There were in use, and embodied in specifications, many different kinds of splices, some of which were obviously very inefficient. The growing shortage of full-length material made the matter of increasing importance, and several series of tests were run both in this country and in Great Britain.

The following report is based on tests on about 150 spliced beams and 150 unspliced beams, each spliced beam being matched to an unspliced one by being cut alongside of it out of the same plank. The beams were all Douglas fir, kiln dried, and of good quality, $1\frac{5}{8}$ by $2\frac{3}{4}$ inches in cross section, and the splices were made up by hand, using certified hide glue. The dowels

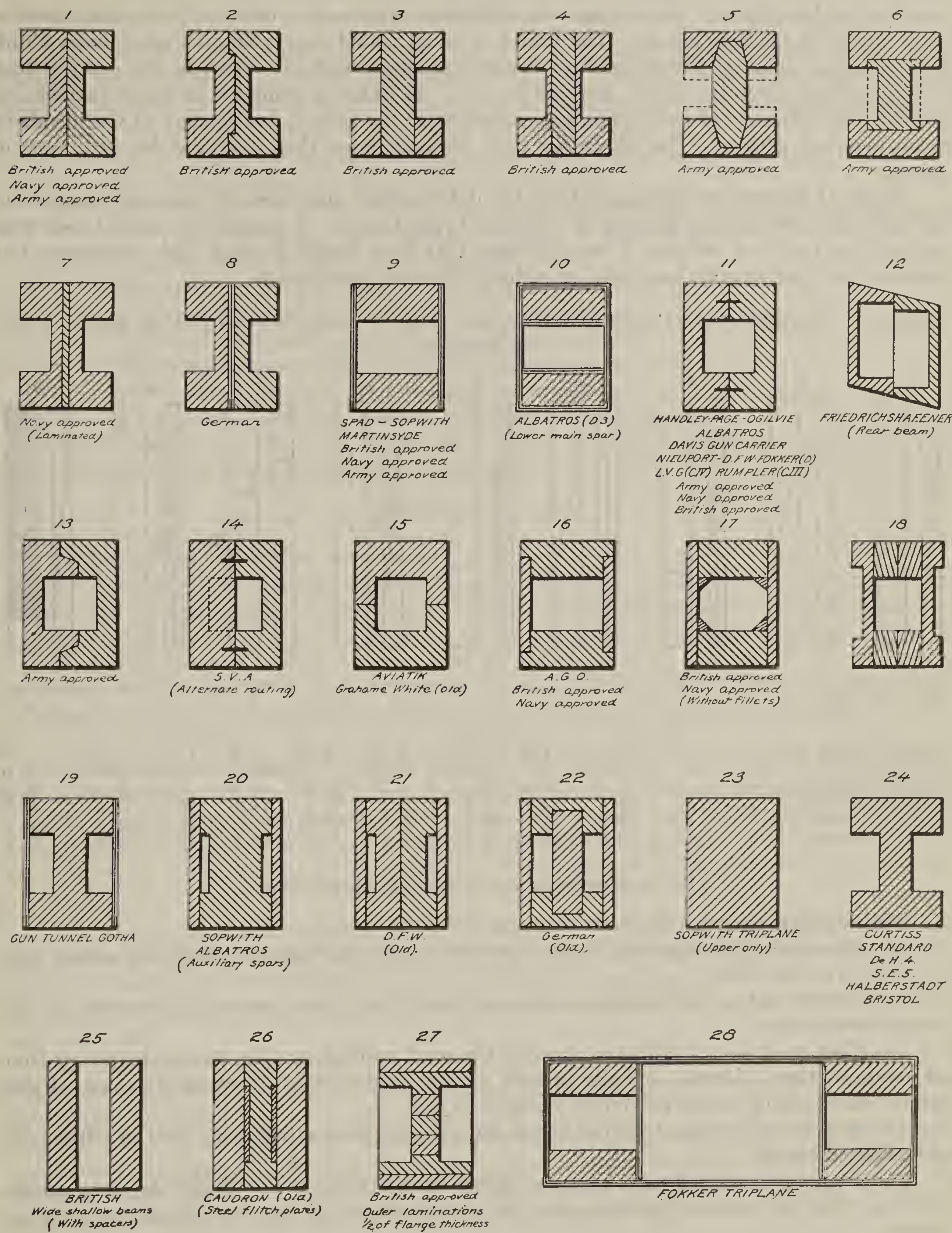
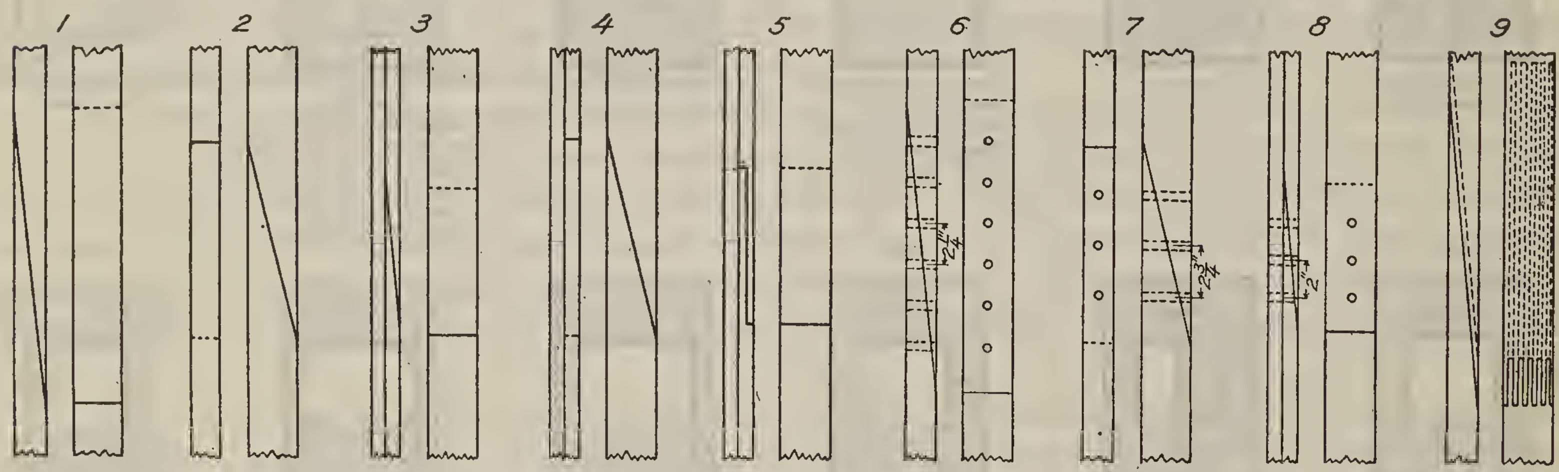


Fig. 47.—Typical built-up wing spars.

were also of Douglas fir. In no cases were clamps or tape used to reinforce the splices; neither were any of the splices bolted. The beams were all tested over a 60-inch span under third-point loading, thus producing uniform bending moment, without shear, in the central third of the span, in which the splices were all located. In order to eliminate as many variables as possible, the efficiency of each splice was calculated in per cent of the strength of the unspliced beam matched with it. The efficiencies thus obtained were then averaged for each type of splice.

Table 14 presents in condensed form the data secured and shows the average, maximum, and minimum efficiencies of each of the nine types tested. A number of these types were selected for test, not because it was thought that they would develop high efficiencies but because they had already been used or included in some specification.

TABLE 14.—*Strength of wing beam splices—spars, $1\frac{5}{8}$ by $2\frac{3}{4}$ inches in cross section; dowels, $\frac{1}{2}$ inch in diameter.*



Wing beam splice No.	1	2	3	4	5	6	7	8	9
Length of splice, inches	16. 25	11. 00	8. 125	5. 50	8. 50	16. 25	11. 0	8. 125	16. 25
Slope of splice	1 in 10	1 in 4	1 in 10	1 in 4	....	1 in 10	1 in 4	1 in 10	1 in 10
Glued area, square inches	44. 8	18. 43	22. 4	9. 22	*23. 40	44. 80	18. 43	22. 40	85. 60
Minimum efficiency	49. 5	17. 5	77. 7	39. 1	74. 1	74. 9	19. 6	72. 0	50. 0
Maximum efficiency	88. 0	53. 2	105. 5	86. 5	91. 0	107. 0	61. 4	123. 5	100. 7
Average efficiency	73. 0	34. 0	90. 0	66. 7	81. 0	86. 4	38. 7	100. 0	75. 9

* Does not include two end areas, 2×(2.75×0.406), 2.23 square inches.

The conclusions drawn from the tests are as follows:

(1) A laminated beam spliced in one lamination is stronger than a solid beam spliced with the same type and slope.

(2) Dowels add to the strength of splices from 10 to 20 per cent on the average for the spliced beams tested.

(3) Plain scarf joints, with the plane of the scarf vertical, are the most satisfactory from all points of view. Dowels or bolts provide a great deal of residual strength in case of glue failure, while adding to the maximum strength as well.

(4) In general, a slope of scarf of one in ten will provide a satisfactory joint in either solid or laminated beams.

It is very interesting to note that the British have arrived at practically the same conclusions and that the standard British splice has a slope of one in nine, with dowels or bolts and dowels.

STRUTS.

The discussion and conclusions presented in the following paragraphs are based upon strength tests conducted on about 400 struts of various types, some of which were made of accepted material and others of material rejected by airplane inspectors for one reason or another.

Among the principal objects of these tests are the following:

(*a*) To check the individual designs and the factors of safety developed.

(*b*) To determine the variability of the material.

(*c*) To study the effect of spiral grain and other defects upon the properties of the finished struts and to develop methods of inspection.

Tests have been made upon the following kinds of struts:

Standard J–1 inners, accepted and rejected, spruce.
Standard J–1 outers, accepted and rejected, spruce.
Standard J–1 center, accepted and rejected, spruce.
DH–4 inners, accepted and rejected, spruce and fir.
DH–4 outers, accepted and rejected, spruce and fir.
F5–L outers, accepted, spruce (laminated, $2\frac{1}{4}$ by $6\frac{3}{4}$ inches).

All of these except the F5–L struts were solid. The F5–L struts are laminated, with three laminations, of which the center one is lightened by means of two oblong lightening holes.

METHODS OF TEST.

The following kinds of test were made:

(1) Standard-screw testing machine, used for making column tests on struts with the regular end fittings supplied by the manufacturer. Slow, uniform speed of compression. A number of these struts were tested up to the maximum load repeatedly without any injury.

(2) Standard-screw testing machine, used for making column tests on struts, with special knife-edge and fittings, which provided practically perfect "pin ends." Slow, uniform speed of compression. Many of the struts tested repeatedly to maximum load without injury.

(3) Dead-load tests on struts carried nearly to the maximum load.

(4) Special tests in hand machines designed for use in the inspection of struts. These machines show the maximum load direct or allow it to be calculated from the stiffness in bending.

The results secured are presented according to groups of struts as tested, and the conclusions drawn are presented at the end of the discussion for each group.

TESTS ON STANDARD J–1 STRUTS.

The first series tested consisted of 60 J–1 struts, outers, inners, and centers, all spruce. These were accepted stock and were tested principally to check the designs and determine the quality of the spruce. The following general conclusions were drawn:

(1) The quality of the spruce was satisfactory, except that 10 struts had a specific gravity less than 0.36.

(2) The struts were all slender enough to enable the maximum load to be determined without injury to the strut. In fact it was found possible to load the struts repeatedly to maximum load without injury.

(3) It was found that the ball-and-socket joints provided by the manufacturer offered some resistance to the free deflection of the struts. This resistance would probably not be present in actual flight, due to vibration. The knife-edge fittings were found to obviate this source of error and were adopted as the standard fitting for future tests.

The loads sustained by the various classes are as follows:

	Minimum.	Maximum.	Average.
Front outers	935	1, 510	1, 203
Front inners	1, 620	2, 980	2, 325
Rear outers	830	1, 505	1, 148
Rear inners	1, 610	2, 965	2, 067

The average moisture content for the outers was 8.2 per cent and for the inners, 8.3 per cent.

In order to form a basis for comparing the variations in the individual struts with normal variations in the spruce itself, an analysis of the stiffness of 500 specimens of spruce was made, and it was found that the average variation of the individual moduli of elasticity from the average of them all was 15 per cent. This average variation was secured as follows: The difference between each individual modulus of elasticity and the average modulus was expressed in per cent of the latter, and these percentage differences were then averaged to secure the average variation.

The average variation from the average strengths for the struts compares favorably with this figure of 15 per cent and is tabulated by strut classes:

	Per cent.
Outers	13
Inners	16
Centers	12

The individual variation of the maximum and minimum from the average strengths is as follows, again by classes of struts:

	Per cent.
Outers:	
Minimum	30
Maximum	30
Inners:	
Minimum	27
Maximum	40
Centers:	
Minimum	34
Maximum	14

In general, the struts followed Euler's law as well as could be expected, except that the ideal load deflection curve, OABC, figure 48, was modified in the actual tests to a curve more nearly represented by ODBC. This was in all probability due to unavoidable eccentricity of fittings and loading. According to the Euler theory the elastic curve of a slender column is a sine curve. The actual curve, as determined by direct measurement, approaches very near to the theoretical curve of Euler.

TESTS ON REJECTED J–1 STRUTS.

This group of struts, spruce outers and inners, was rejected by Government inspectors, and tested primarily to determine the effect of defects upon the strength of the struts and to study means of inspection. Standard methods of test were followed. The general conclusions drawn are as follows:

(1) As a group, these struts were not as good as the 40 accepted struts previously tested. A larger portion of the rejects broke suddenly and a larger proportion broke without preliminary compression failure.

(2) Forty-one of the rejected struts appeared to the laboratory staff making the tests as satisfactory regarding both direction of grain and specific gravity. With one exception, the weakest of these 41 was as strong as the weakest of the 40 accepted struts previously tested. Further, the average of these 41 rejected struts was nearly as good as that of the 40 accepted ones.

(3) There were 18 struts whose diagonal or spiral grain was between 1 in 15 and 1 in 20. Of these, 16 compared favorably with the 41 discussed in the two preceding paragraphs.

(4) A total of 57 (16 plus 41) of the 100 rejected struts compared favorably with the 40 accepted struts previously tested.

(5) It is possible to segregate the acceptable struts from lots of rejected struts by means of simple strength tests if the passing values are appropriately chosen from preceding laboratory tests on struts like those in question.

(6) The limiting grain may safely be reduced to 1 in 15 without causing a reduction in the factor of safety, provided that strength tests and appropriate passing values are imposed. Such a plan of inspection by test would undoubtedly increase the quality and percentage of acceptance.

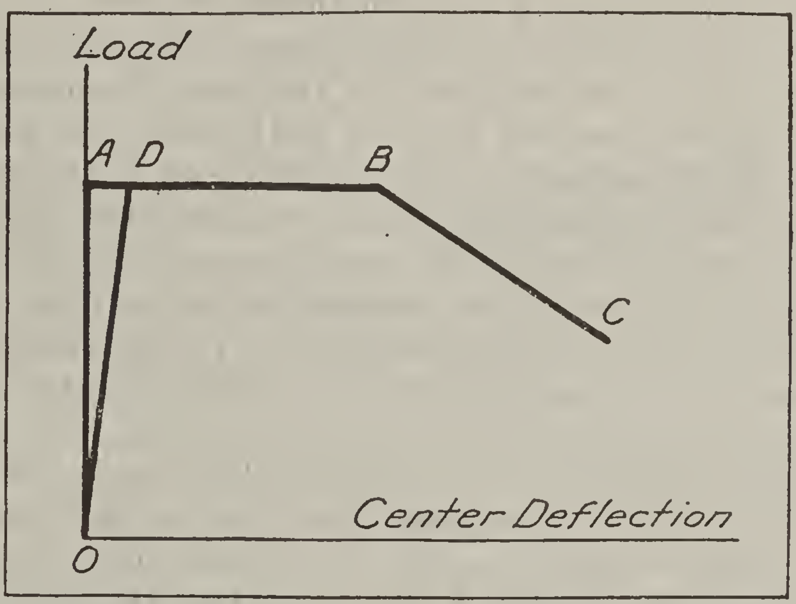


Fig. 48—Load deflection curves for slender struts.

TESTS ON STANDARD DE HAVILLAND STRUTS.

The purpose of the tests was, in general, to check the design calculations and afford a direct comparison between spruce and Douglas fir when used as struts. Half of the struts were tested in the machine in the usual manner and the other half were tested in a special dead-load apparatus. A summary of the results follows:

(1) With the exception of one strut, a spruce stick notably below specification both as to spiral grain and density, all the struts developed maximum loads greater than that for which they were designed.

(2) The weakest of the fir struts was notably low in density, but still it was considerably stronger than the calculated load.

(3) There was practically no difference in the average strengths of the spruce and the fir struts; but there was wider variation between the minimum and maximum values for spruce than for fir. Without exception, the spruce struts were lighter than the lightest fir strut. For unit weight (of strut) the spruce struts were 17½ per cent stronger on the average than the fir.

(4) In the dead-weight test all of the struts, with one exception, were stable; that is, if deflected by a side push (when under the weight of 3,200 pounds chosen for the test, which was just under the crippling load for the weakest strut), they would come back upon removal of the push. The exception was the weakest strut, which was unstable at a dead-weight of 3,030 pounds.

(5) Notwithstanding the general low specific gravity of the fir struts, the maximum loads which they sustained were high, and it would seem safe to reduce the limit from 0.47 to 0.45 for struts of the same size as spruce and to use fir interchangeably with spruce.

TESTS ON REJECTED DE HAVILLAND STRUTS.

These tests were primarily made in connection with the development of strut-testing machines and inspection by actual test. There were 70 spruce and 70 Douglas fir struts, all rejected by Government inspectors for one reason or another. One hundred had been rejected for spiral grain and the other 40 for miscellaneous defects, which, under actual test, did not influence the failures at all. The results of these tests confirmed the conclusions drawn from previous tests, both as to the need and practicability of a strength specification and test, and the limits of slope of grain and specific gravity for Douglas fir already mentioned. In addition, careful study was made of the variation of spiral grain along the length of the strut and its effect upon the maximum load, and as a result of this study the conclusion has been reached that for struts of uniform cross section, like the D-H struts, the most severe requirements for straightness of grain should be limited to the middle third and to the tapered ends and that the requirements for the balance of the strut can be more lenient.

The final recommendation concerning the slope of grain is that, assuming the determination of the maximum load for each strut and no reduction in the factor of safety, the steepest slope allowed in the center third and in the tapered ends be 1 in 15 and that the passing load for struts with a slope between 1 in 15 and 1 in 20 be set higher than for straighter-grained struts. Struts with a slope between 1 in 15 and 1 in 20 at the center third and at the tapered ends and showing the larger load specified for them are to be allowed a slope of 1 in 12 for the remainder of the strut; also, struts with straighter grain than 1 in 20, which also show the larger load specified for struts with steeper slope, may have a slope of 1 in 12 outside the middle third and the tapered ends; but struts having a grain straighter than 1 in 20 in the middle third and in the tapered ends and which meet the lower load requirements specified for them, but do not meet the higher load specified for the struts with the steeper slope, may be allowed to have grain with a slope of 1 in 15 or straighter in the remainder. The requirement for greater load in the case of the steeper slopes is put in to insure against possible greater variability in shock resistance of this material.

TESTS ON STANDARD F5–L STRUTS.

The main purpose of these tests was to determine whether or not they fall in the class of slender struts and can be loaded to their maximum loads without injury. These struts are built up of three laminations each, the center laminations being lightened by two oblong lightening holes. They are $2\frac{1}{4}$ by $6\frac{3}{4}$ by 102 inches. It was found that they could be tested up to their maximum load without injury, and it was also found possible to calculate the maximum loads by means of stiffness determinations based upon simple bending tests. The details of these methods will be described in the following paragraphs:

TWO NONINJURIOUS TEST METHODS FOR INSPECTING STRUTS.

Two noninjurious methods of test for determining the ultimate strength of interplane struts have been developed as a result of the series of tests which have been described in the preceding pages. Both methods are applicable to routine inspection tests in the factory, and the equip-

ment needed is simple and cheap. Both methods are applicable to slender struts (all the struts so far have fallen in this class).

In order to determine the limiting slenderness ratio, $\frac{L}{r}$, governing the use of these two methods for solid spruce and Douglas fir struts, tests were made upon three spruce and three fir struts, as follows: They were first tested full length, $\frac{L}{r}$ about 165, and were then successively shortened to $\frac{L}{r}$ ratios of 140, 120, 100, 90, and 80, and tested at each length by both methods. As a result of these tests the conclusion is reached that for spruce the limiting slenderness ratio is about 100 and for Douglas fir about 90.

Three types of machine have been built and tried out satisfactorily. In the first two types the strut is actually loaded up to the maximum load. In the third type the modulus of elasticity is determined by means of a simple beam test well within the elastic limit and the maximum load calculated by a simple conversion formula.

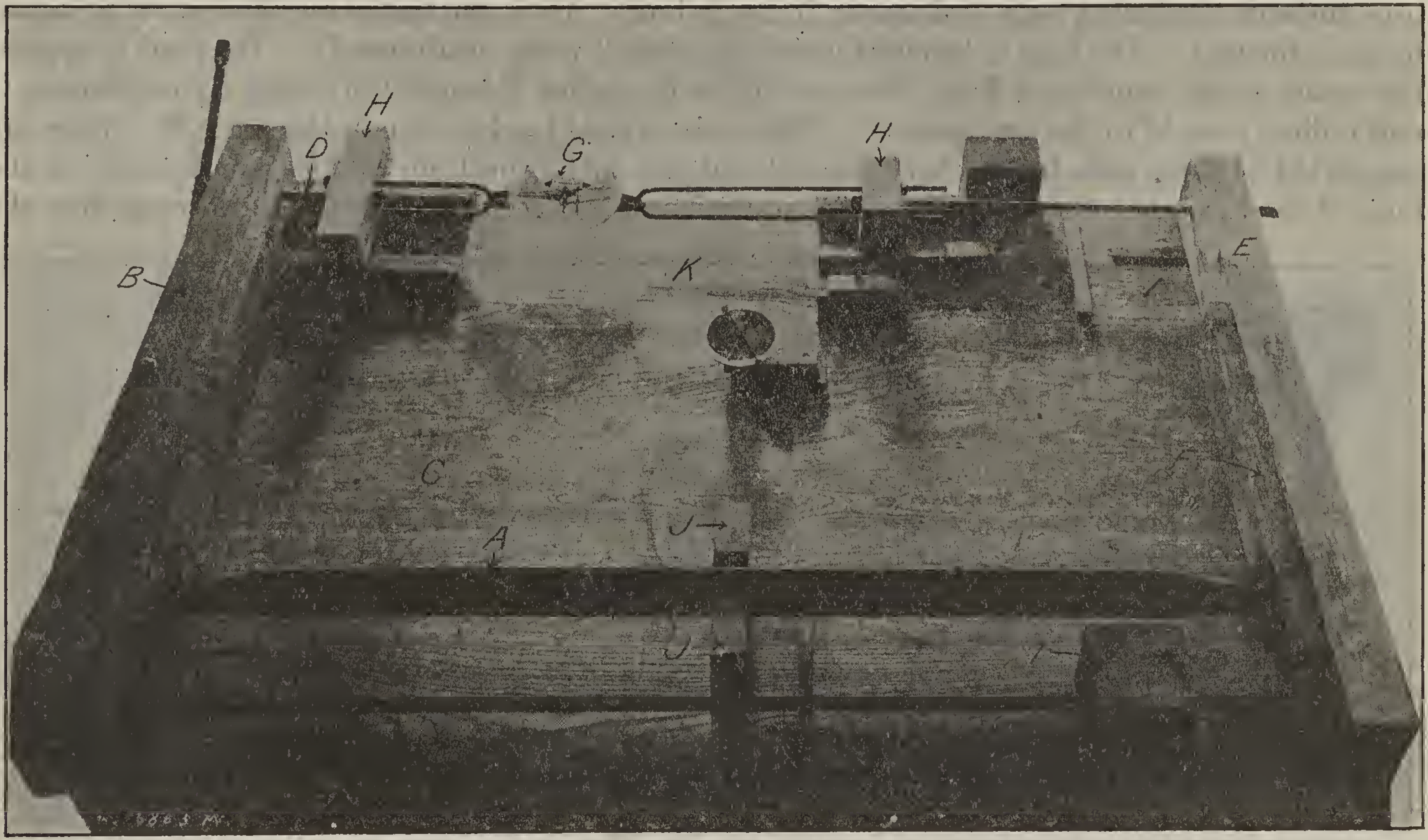


Fig. 49.—Homemade strut-testing machine, first design.

The first machine (fig. 49) employs the lever principle and is especially suitable for larger strut loads, say over 5,000 pounds. A (fig. 49) is a strut in place for testing; B is a base rigidly fastened to the top of table C; it affords support for one end of the strut and also for the pulling screw D. E is a lever, by means of which the pull (multiplied) is brought to bear on the strut as strut load. F is a knife-edge fulcrum; and G a spring dynamometer. H and I are supports for pulling rod and fulcrum rod, respectively. J–J are the stops at either side of the middle of the strut to limit excessive deflection of the strut through careless operation. The dial K is not a part of the machine for making the proposed acceptance tests. It was used for measuring strut deflections in another investigation. The dynamometer (John Chatillon & Sons, of New

York) is of 1,500 pounds capacity. It is graduated in 25-pound intervals, and 5 pounds can be estimated easily. The pulling rig is an ordinary carpenter bench vise screw, handle, etc.; the screw has eight threads to the inch.

The second machine (fig. 50) is of the direct-pull type without multiplying lever, especially suitable for the smaller strut loads, say under 5,000 pounds. It consists of a long shallow box,

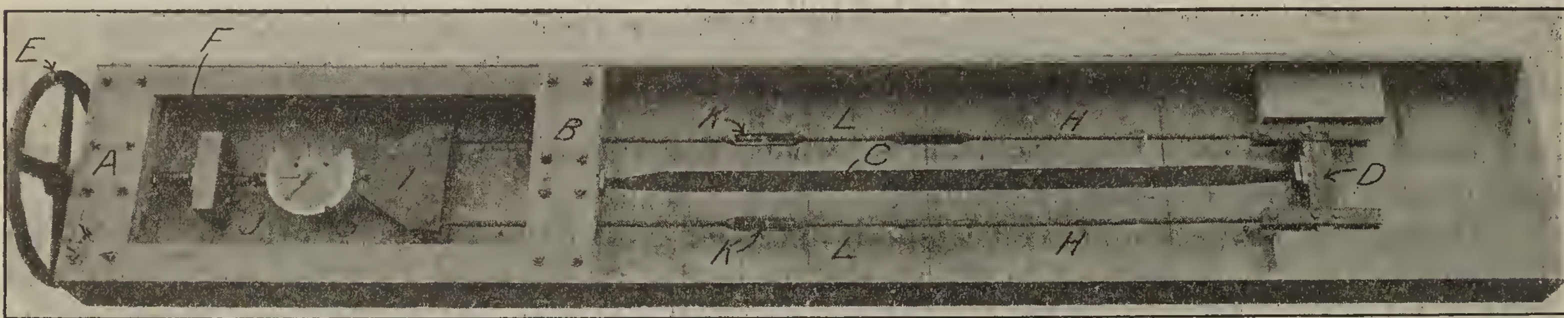


Fig. 50.—Homemade strut-testing machine, second design.

into one end of which a rigid and strong frame is built; AB is the frame mentioned; C is a strut in place for test. The load is brought upon the strut by the headpiece D. The load is applied by means of the handwheel E on the screw F; it is applied through the spring dynamometer G and pulling rods H to the headpiece D. The rods extend freely through the piece B. They are supported at their ends by the headpiece D and the part I, both on castors which track on the floor of the box when the machine is used in horizontal position. J is wood block encircling the

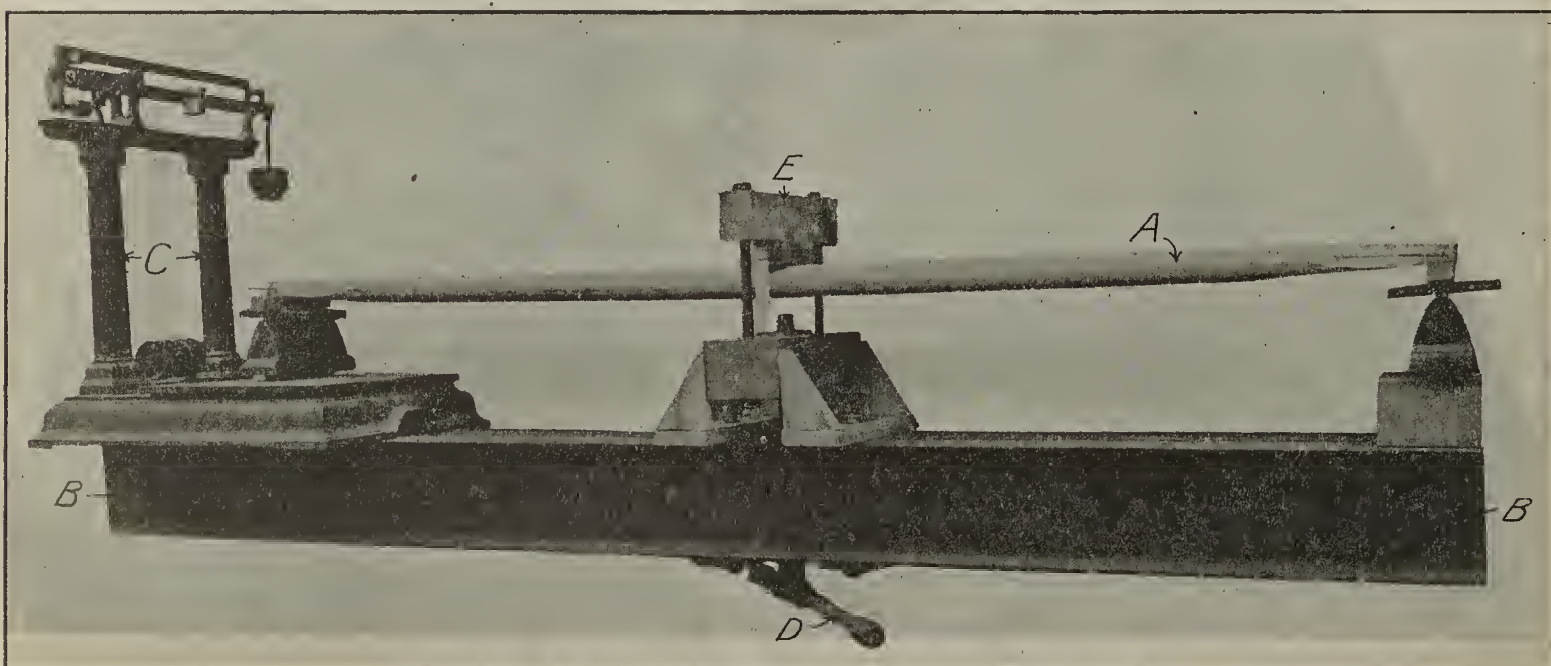


Fig. 51.—Beam machine for strut testing.

pulling nut. It prevents the nut from turning and affords attachment for the dynamometer. Adjustment for different strut lengths is afforded by the turnbuckles K and the distance rods L.

The third machine (fig. 51) is a "beam machine" for the second method of determining strut strength. A is the strut in place for testing; BB are I beams forming the base of the entire appliance; they support the weighing scale C, the loading screw D, and one end of the strut. The middle deflections of the strut are measured by means of the usual device, a thread stretched between two points on the strut just over the supports and a suitable vertical scale just behind this thread and fixed to the strut or to the loading block E.

Discussion of noninjurious test methods.—Reference has been made to a simple formula used to calculate the maximum load of a strut from a smaller load and the corresponding deflection in a bending test (the method illustrated in fig. 51). The following discussion will show how this formula is developed.

Euler's column formula seems to be in most common use for calculating the maximum strength of interplane struts, and the method under discussion is based mainly on that formula. It is:

$$Q=\frac{C\pi^2 EI}{L^2} \tag{1}$$

Where Q = Total crushing strength of column in pounds.
C = A coefficient depending on the character of the end bearings (free or fixed).
E = Modulus of elasticity in pounds per square inch.
I = Moment of inertia.
L = Length of column between bearings in inches.

The deflection in a strut supported flatwise near its ends and then subjected to a cross-bending load, such that the strut (as a beam) is not overstrained, is given by the formula:

$$d=K\frac{Pl^3}{EI} \tag{2}$$

Where d = Deflection at center in inches.
K = A coefficient depending on loading and manner of support of the strut as a beam.
P = Any moderate (beam) load, not overstraining the beam, in pounds.
l = Span in the beam test in inches.
E = Modulus of elasticity in pounds per square inch.
I = Moment of inertia.

For any given strut equations (1) and (2) may be equated by solving for EI in both cases, thus:

$$EI=\frac{QL^2}{C\pi^2}=\frac{KPl^3}{d}$$

Solving for Q gives the formula:

$$Q=\frac{CK\pi^2 Pl^3}{L^2 d} \tag{3}$$

For struts on knife-edges supports C = 1. Struts (on ball-and-socket supports, pin supports, and the like) in flying airplanes are subjected to vibration which breaks down the friction at the supports and makes the supports equivalent to knife-edges. Hence it seems wise, as in practice, to calculate the ultimate strength of airplane struts as though knife-edge supported; that is, with C = 1. In regard to the most suitable kind of loading of the strut as a beam, only center and third point were considered; others were regarded as impractical. By actual trial of 12 struts it was found, contrary to expectation, that center loading gave the better results; accordingly, that loading was finally decided upon. For such loading and simple nonrestraining supports, K = 1/48. Hence equation (3) becomes

$$Q=\frac{.206l^3}{L^2}\times\frac{P}{d} \tag{4}$$

which is the final form. It will be noted that P and d (or their ratio) are the only quantities for which test must be made in order to furnish the value of Q for any particular strut. $\frac{P}{d}$ is the center load per inch of deflection; it is therefore a measure of the stiffness of the strut.

For struts not uniform in cross section or composition the Euler (column) formula and the beam deflection formula still hold. Appropriate mean or average values of E and of I must, of course, be used in each, but whether or not these average values in the column formula are respectively equal to those in the deflection formula, thus permitting their cancellation or elimination, can not be answered positively for all nonuniform struts. It is believed that the answer is affirmative. There is affirmative evidence from tests of 20 tapered solid struts (10 outer and 10 inner struts for the J–1 airplane), also from tests on 5 built-up struts (5 pieces, plywood covered); that is to say, the second method of test, based on formula (4), was applied to these struts and very good results were obtained.

Comparison of two test methods by actual trials.—Thirty-five struts were tested by the beam method and for comparison by the column method also. The tests by the beam method were made with the struts on knife-edge supports. The results are recorded in the columns marked Q_1 (table 15). The results by the column method are recorded in columns marked Q_2 (table 15). The per cent differences between Q_1 and Q_2 appear in the following columns. They are decidedly small, and the test verification of the theory of this second method is highly satisfactory. The table includes solid struts of spruce and Douglas fir, both of uniform and tapered section, and struts of uniform section built up of spruce and birch.

TABLE 15.—*Maximum or crippling loads for certain struts determined by measurement in column tests and by calculation from cross-bending tests.*

(*a*) Solid struts uniform in section.

No.	Species.	Q_1	Q_2		$\frac{Q_1-Q_2}{Q_1}$		Average grain.	
			l=52 inches.	l=60 inches.	l=52 inches.	l=60 inches.	Spiral.	Diagonal.
DH–4 inners		*Pounds.*			*Per cent.*	*Per cent.*		
G–41	Spruce	5,175	5,380	5,390	−4.0	−4.1	65	95
G–42	do	6,350	6,420	6,530	−1.1	−2.8	65	50
G–56	do	5,125	5,270	5,530	−2.8	−7.9	80	80
G–57	do	4,375	4,310	4,575	+1.5	−4.6	14	60
G–64	do	3,445	3,640	3,645	−5.6	−5.8	25	100
DH–4 outers:								
G–70	Fir	2,075	2,040	2,080	+1.7	−0.2	30	80
G–74	do	2,240	2,200	2,180	+1.8	+2.7	15	95
G–76	do	2,560	2,520	2,570	+1.6	−0.4	39	21
G–79	do	2,020	2,035	2,060	−0.7	−2.0	18	80
G–80	do	2,460	2,485	2,510	−1.0	−2.0	16	95
J–1 inners:								
D–1	Spruce	2,540	2,570	2,510	−1.2	+1.2		
D–13	do	1,800	1,750	1,820	+2.8	−1.1		
D–14	do	1,975	1,920	1,945	+2.8	+1.5		
D–17	do	1,950	1,920	2,030	+1.5	−4.1		
D–2	Fir	2,170	2,220	2,200	−2.3	−1.4		
J–1 outers:								
D–19	Spruce	1,450	1,425	1,430	+1.7	+1.4		
D–20	do	1,235	1,195	1,200	+3.2	+2.8		
D–21	do	1,060	1,010	1,030	+4.7	+2.8		
D–7	do	1,415	1,355	1,385	+4.2	+2.1		
D–8	do	1,390	1,385	1,360	+0.4	+2.2		
Average					2.4	2.7		

Q_1=Max. load as measured in column-bending test.
Q_2=Max. load as calculated from cross-bending test.

$$Q_2=\frac{2Pl^3}{48DL^2}$$

D=Deflection at load P in cross bending.
l=Span in cross bending.
L=Effective length in column bending.

TABLE 15.—*Maximum or crippling loads for certain struts determined by measurement in column tests and by calculation from cross-bending tests*—Continued.

(*b*) Solid struts tapered (Span=l=64 inches).

No.	Species.	Q_1	Q_2	$\frac{Q_1-Q_2}{Q_1}$
J-1 inners:		*Pounds.*	*Pounds.*	*Per cent.*
D-1	Spruce	2,275	2,450	−7.1
D-13	do	1,700	1,720	−1.2
D-14	do	1,790	1,835	−2.5
D-17	do	1,775	1,750	+1.4
D-19	do	1,400	1,430	−2.1
D-2	Fir	2,030	2,120	−4.4
J-1 outers:				
D-20	Spruce	1,165	1,210	−3.9
D-21	do	1,000	1,040	−4.0
D-7	Fir	1,300	1,330	−2.3
D-8	do	1,315	1,350	−2.6
Average				3.2

(*c*) Built-up struts,* uniform in section (span=l=60 inches).

No.	Species.	Q_1	Q_2	$\frac{Q_1-Q_2}{Q_1}$
		Pounds.	*Pounds.*	*Per cent.*
J-14	All spruce and birch	4,250	4,160	+2.1
J-15				
J-16		4,815	4,710	+2.2
J-17		3,760	3,600	+4.2
J-18		3,500	3,540	−1.1
J-19		3,425	3,440	−0.4
Average				2.0

* The core was a double box made of spruce; it was covered or stream lined with two-ply spruce; the inner ply was longitudinal, about one-eighth inch thick, the outer circumferential, about one-thirty-second inch thick. Other dimensions were as for DH-4 inners.

It will be noted that many of the struts were tested on two spans. One span was practically the maximum which the strut afforded. The two spans were tried out to ascertain whether choice of span is important. As expected, the choice was unimportant with struts of uniform cross sections, but with tapered struts the longest span gave best results. Several struts were tested twice on the same span. The second time turned over—that is, the side which was the upper in the first test was the lower in the second. The values of $\frac{P}{d}$ in the two tests were practically alike in each case.

A high degree of skill is not necessary in using the cross-bending test for inspecting struts, but for good results care should be taken about details. Both ends of the strut should be supported in such a way that bending can occur without the ends slipping on the supports. The supports should be such that there is no doubt where the points of support are, because the exact value of span is required in formula (4). The bending load P is relatively small compared with the maximum (100 to 400 pounds for struts so far tested). Hence, a weighing apparatus correct to 1 or 2 pounds should be provided. The deflection should be read with reference to points on the strut immediately over the support and not on the machine. For best results a single value of $\frac{P}{d}$ should not be relied upon. Good practice is to read loads and deflections

for a load deflection graph. The mean straight line gives the best value of $\frac{P}{d}$ for use in the formula. Of course, the loadings should not be carried to the elastic limit. In the tests of J–1 and DH–4 struts deflections up to one-half inch were used. This was really more than necessary. All that is needed is enough of the (straight) load deflection graph to be certain of its slope, $\frac{P}{d}$.

MISCELLANEOUS STRUT TESTS.

Tests of struts stream lined with plywood.—Seven struts of two distinct designs were tested as square-ended columns and compared directly with solid spruce struts of the same gross area and solid spruce struts of the same weight, also tested as square-ended columns. The sections of the built-up struts are shown in figure 52a and b. The test length was 5 feet. As was to be expected, the design shown in figure 52a did not develop satisfactory strength, and after testing four struts the design shown in figure 52b was developed and three struts made up, using, respectively, birch, soft maple, and red gum plywood. These struts developed about double the strength of the other type, and appear to be rather well balanced (as square-ended columns), since one of them failed by shearing of the spruce web.

The plywood struts were naturally larger than solid spruce struts of the same strength and shape, although lighter, and consequently would create greater wind resistance or drift.

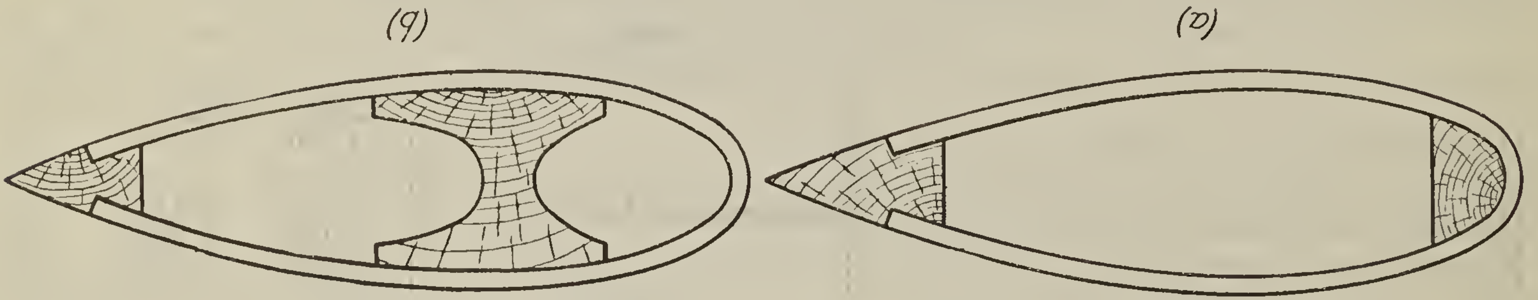


Fig. 52.—Spruce and plywood struts.

In order to reach an equitable basis of comparison it was necessary to consider both weight and drift. Assuming an air speed of 80 feet per second and that 1 pound of resistance is equivalent to 6 pounds of weight, the equivalent weight of the plywood struts was calculated to be 91 per cent of that of the solid struts (of the same strength and shape) at this speed.

Naturally at higher speeds the advantage of the plywood struts is correspondingly less, disappearing entirely long before present maximum speeds are reached. The average weight of the plywood struts was 3.91 pounds and the average actual load sustained was 9,700 pounds (as square-ended columns).

Tests on struts covered with bakelized canvas.—Tests were made on 24 spruce struts, more or less cross grained, and covered with bakelized canvas (micarta). The external dimensions of all the struts were alike, but half were covered with two layers of canvas and the other half with four layers; the former having, therefore, more wood in them than the latter. All the struts were tested in column bending for maximum load without injuring them. All were subsequently tested to failure, 16 with the canvas partially or wholly removed.

Since the modulus of elasticity of bakelized canvas is lower and its specific gravity much higher than that of spruce, one would expect this material to be a poor substitute for spruce in struts, so far as total strength and strength per unit weight of strut is concerned. All tests made verify this expectation, but the canvas covering improved the quality of the defective spruce struts in one respect, namely, the capacity of the strut to withstand severe shock. This conclusion is based on the fact that the deflection at failure for eight covered struts was considerably greater than for four struts stripped.

The struts covered with two layers of canvas were stronger than those with four because there was more wood in them and they were much stronger per unit of weight than the latter.

Struts covered with canvas were but little stronger than the same struts stripped of canvas. The covered ones were weaker than the stripped ones per unit weight of strut. Further, it is computed that the canvas-covered struts were weaker than spruce struts of the same size would have been.

Comparisons with 40 J–1 struts previously tested show that the covered struts were not as high in total strength or strength per unit weight as the plain struts.

Several struts had the outer layer of canvas removed for some distance from the ends, and these struts so stripped were to all intents and purposes as strong as they were originally.

Effect of taper on the strength of struts.—Tests were made on 40 solid struts to determine the effect of taper. These struts were of spruce and Douglas fir. Some were of the sizes and shapes corresponding to DH–4 inners and outers and the others of the sizes and shapes corresponding to the central sections of Standard J–1 inners and outers. (It will be remembered that the J–1 struts have a central section about 0.46 the length of the strut, which is of uniform section, the taper starting at the ends of this section and running in a smooth curve to the ends.) These 40 struts were all first tested for maximum load while of uniform section. They were all tapered to the geometrical form of the J–1 taper and again tested for maximum load. Finally the DH–4 struts were given a very pronounced taper and tested a third time for maximum load. The results of the series of tests are presented in condensed form in table 16.

TABLE 16.—*Effect of taper on the strength and weight of struts.*

Lot No.	Number of struts.	Change due to first taper.			Change due to second taper.		
		A.	B.	C.	A.	B.	C.
		Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	3	− 4.9	+0.6	+5.7	−22.2	−32.3	−6.6
2	3	− 4.4	0.0	+4.4	−26.7	−23.5	−3.9
3	5	− 3.7	−1.5	+2.1	−17.8	−20.3	−3.6
4	5	− 5.1	−2.0	+3.1	−18.8	−22.1	−4.6
5	7	− 8.1	−3.1	+4.8	....	....	....
6	5	− 9.0	−3.5	+6.2	....	....	....
7	7	− 9.7	−2.4	+7.9	....	....	....
8	5	−11.2	−3.1	+9.0	....	....	....

A represents change in weight due to taper.
B represents change in maximum load due to taper.
C represents change in maximum load per unit weight of strut, due to taper.

Lots 1 to 4 were DH–4 struts, and lots 5 to 8 of J–1 size.

The maximum load per unit weight was increased by the first taper from a minimum of 2.1 per cent for lot 3 to a maximum of 9 per cent for lot 8. The weighted average increase was 5.5 per cent.

It will be noted that the second taper reduced the strength weight ratio as well as the maximum load.

DESIGN AND MANUFACTURE OF BUILT-UP STRUTS.

The following general discussion is based upon the results of several hundred thousand tests on wood in various forms, as well as upon the experience gained in the design, manufacture, and test of struts of various types. While much of the discussion is quite obvious, it is believed to be pertinent.

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Built-up struts possess a number of advantages and disadvantages as compared to the solid one-piece construction, some of which are as follows:

Advantages:

- Use of small pieces of material.
- More effective distribution of material.
  - (*a*) By routing.
  - (*b*) By using materials of different density.
- Possibility of using defective material.
- Complete failure may not occur with failure of one lamina.

Disadvantages:

- Greater warping or bowing if pieces are not rightly selected and well manufactured.
- Greater difficulty in manufacture.
- Greater time required for manufacture.

One of the main advantages of built-up struts is the possible use of smaller dimension material with its corresponding lower cost and greater availability. It is further a matter of common observation that many of the larger pieces which contain defects such as to make them unsatisfactory for use as a single unit would yield smaller pieces free from defects and suitable for built-up construction. The material near the center of a solid strut contributes but little in proportion to its weight to the maximum load the strut will carry. Struts lightened by routing at the center, therefore, have the advantage of a greater strength-weight ratio than a solid strut. Enough material at the major axis of symmetry is, of course, necessary to carry the shear, which is greatest along this axis and near the ends of the strut. A built-up strut lends itself readily to routing or lightening at the center.

The taper of solid struts is likewise meant to accomplish a reduction in weight. Weight reduction with a minimum reduction in strength, however, can probably be most effectively obtained through routing in built-up construction. This, however, is more feasible with struts of larger dimension, and probably, all things considered, should not be undertaken on struts whose minor axis is less than $1\frac{3}{4}$ inches. It is common practice in built-up struts lightened in this manner to discontinue the routing at regular intervals, thus leaving a solid cross section at these given points.

Use of materials of different density.—It may be shown that a metal column with proper distribution of material will theoretically withstand a load two or three times greater than a solid wooden section of the same total weight, length, and section boundary. This is based on the assumption that no local buckling takes place. With thin metal walls this assumption would, of course, not be strictly true, as buckling actually does occur. The conclusion is valid, however, that the denser material, with its greater stiffness, may be desirable for struts and is most effective when distributed at the greatest possible distance from the neutral axis. This points to the possible advantages of a combined wood and metal strut and demonstrates in built-up wooden struts, especially the larger sizes, that the use of denser species for the outer portions, with a lighter species for a core, would furnish a possible efficient combination. The use of a combination of species of wood of different density, however, would not be desirable in solid built-up struts of small size, and if used in the larger sizes would require special construction to distribute stresses resulting from unequal changes in dimension and unequal stiffness, as will be considered later.

Tests on combined metal and wood struts are now under investigation, and while very encouraging results have been obtained additional work along this line will be necessary before definite recommendations can be made for production consideration.

Possibility of using defective material.—But little data is available on the effect of defects such as spiral or diagonal grain in the individual pieces on the strength of built-up struts. In connection with the use of spiral grain material for struts, however, it may be noted that the modulus of elasticity is not as greatly reduced by this defect as are the other mechanical properties, and therefore the maximum load in struts which is largely dependent on the stiffness may not be greatly reduced with slopes of grain as great as 1 in 15. In built-up struts containing but one glued surface parallel to the major axis the limitations of defective material should be maintained up to the standard required for one-piece construction. Large struts, however, may be composed of three (or more) sections, as shown in figure 54. The center section, containing the major axis of symmetry, receives little other than shear stress. It is probable that a greater tolerance of grain could be permitted here than in the outer laminations or in one-piece construction. Tests to secure information on this point are necessary and are under consideration.

Possibility of warping or bowing.—One difficulty frequently encountered on the manufacture of built-up struts is the tendency to warp or bow. Practically all wood contains internal stresses to a greater or lesser extent, and failure to take into consideration the factors which influence these stresses contributes largely to the trouble mentioned. As is well known, wood changes dimensions at right angles to the grain to a considerable extent with change in moisture content. Unequal changes in the widths of various laminations causes severe stress in the glued joints and may even cause failure. Among the important factors which cause unequal changes in dimensions in the different laminations are:

(*a*) The use of plain-sawed and quarter-sawed laminations in the same strut.
(*b*) The use of laminations that differ in density.
(*c*) The use of laminations that differ in moisture content.

(*a*) In connection with the use of plain-sawed and quarter-sawed material it may be noted that the shrinkage of Sitka spruce in a radial direction is only about six-tenths of that in a tangential direction. For a given change in moisture, it will therefore be seen that a plain-sawed board would normally undergo a greater change in dimension than would quarter-sawed material. In built-up construction the best results would therefore be expected with quarter-sawed material, as shown in sections 1–a and 1–b, figures 53 and 54. The use of both plain and quarter sawed material in the same built-up part should be avoided.

(*b*) Another factor which may influence the warping of built-up struts is the density of material in adjacent laminations. It has been shown that in general the shrinkage of wood varies directly as the density, and light pieces would therefore, as a rule, retain their shape better than denser ones. The adjacent laminations should be made of pieces of approximately the same density to give the best results, as otherwise considerable stress may be introduced along the glued joints, due to the tendency of the various laminations to change dimensions unequally.

(*c*) Differences in the moisture content of the various laminations at the time of manufacture may also contribute to the warping of built-up struts or other parts. Since wood shrinks with change of moisture content and since all material stored or used under similar conditions will ultimately assume approximately the same moisture content, it follows that differences in moisture content at the time of gluing will cause unequal changes in dimensions which introduce stresses in the glued surface. The fact that all material used in a given laminated member comes from the same stock does not necessarily insure against differences in moisture content between individual pieces. The wide range in the rate of drying of individual pieces, the difference in drying between quarter-sawed and plain-sawed lumber, as well

as the fact that heavy pieces usually dry more slowly than lighter ones, contribute to the differences of moisture content which may be found at any time in a given stock. The position of material in a pile while air seasoning or in the kiln while being dried may also influence the rate of drying and consequently the difference in moisture content between individual pieces at a given time.

The manufacture of built-up struts with proper attention to the various factors which may affect the quality of the product as outlined in the preceding discussion would be more difficult than the manufacture of single-piece members. The time required for inspection

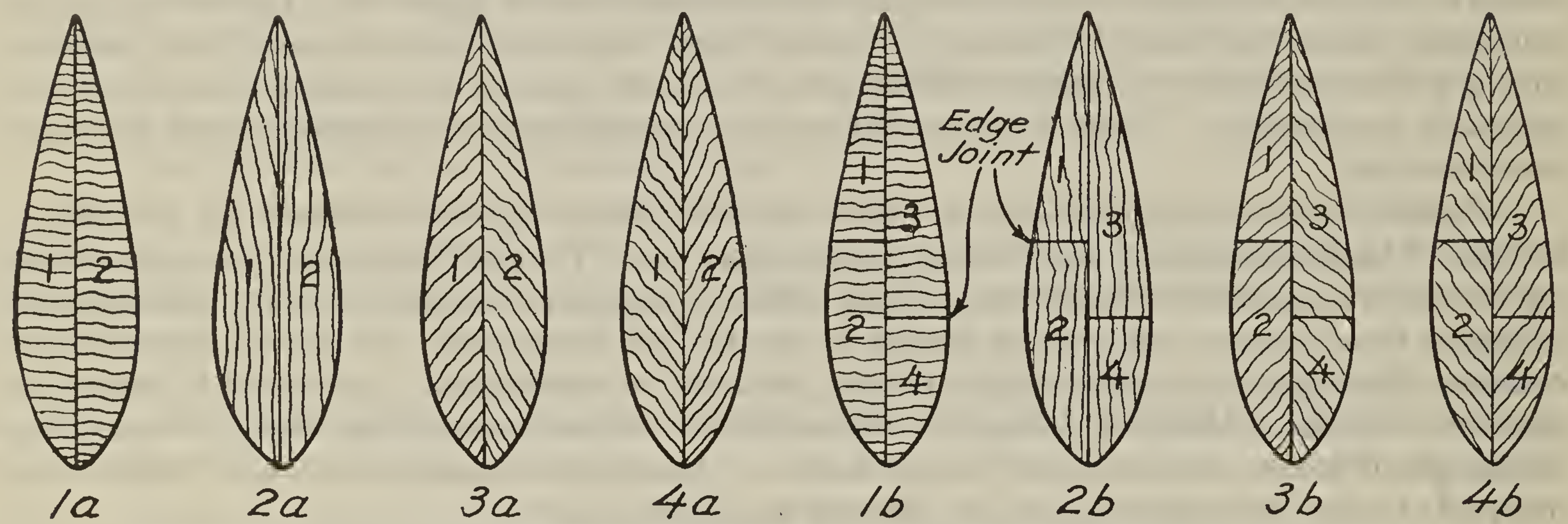

Fig. 53.—Sections of built-up struts, two and four piece construction.

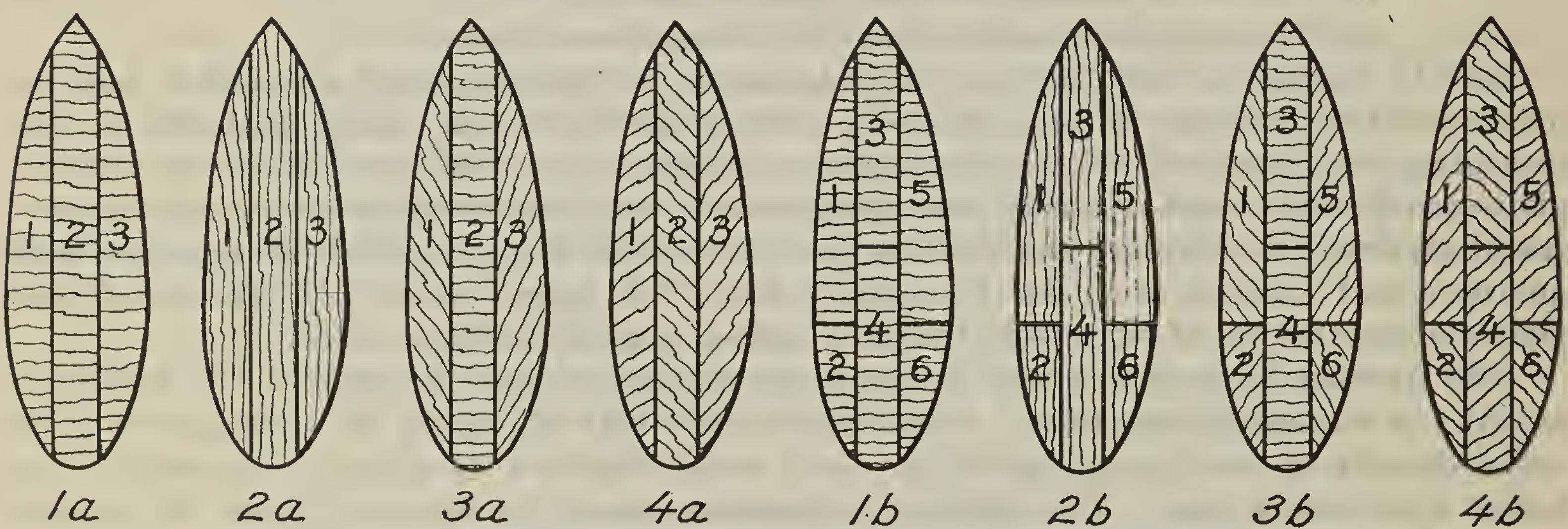

Fig. 54.—Sections of built-up struts, three and six piece construction.

would be increased on account of the greater number of pieces involved and because of the matching required. The gluing would also be an additional item to be considered in manufacture.

The additional work involved in the proper manufacture of laminated struts would probably have a tendency to reduce production, or at least would require greater facilities and more labor for a given output—particularly for struts of smaller sizes. These considerations would tend to offset the lower cost resulting from the more complete utilization of the small pieces.

Static and impact bending tests made on Sitka spruce and a few other species have shown that the position of the growth rings with respect to the faces of the test pieces does not influence the bending strength. No data, however, is available as to the effect of the position of

growth rings on the strength of struts, although it is expeceted that some data along this line will be secured in the near future. From data available at present the position of growth rings in a built-up strut would be expected to affect physical properties, such as the ability to retain shape rather than strength. It is desirable in built-up members that the construction be such as to reduce the stresses to a minimum. This involves the use of material of approximately the same rate of growth, density, moisture content, and direction of growth rings in the cross section.

CONCLUSIONS.

1. The manufacture of built-up struts with a minor axis of 1¾ inches or less is not recommended.

2. (*a*) To secure the best results, the laminations of built-up strut should be approximately of the same moisture content, density, rate of growth, and, in general, except in cases of special design, of the same species.

(*b*) The construction of stream-line struts should be symmetrical about the major axis. It may be noted that symmetry and consequent balance of internal stresses can in some cases be secured without conformity to the exact requirements under (*a*) above.

3. Figures 53 and 54 show recommended sections of built-up struts.

(*a*) Sections 1–a and 1–b in both figures 53 and 54 would be expected to give the greatest freedom from internal stresses and consequent warping.

(*b*) In figure 53 but little difference in ability to retain shape would be expected between sections 2–a, 3–a, and 4–a, and also between 2–b, 3–b, and 4–b.

(*d*) There are a great number of possible combinations of material with different combinations of growth rings, and it is quite possible that other combinations giving modification of types shown should also prove satisfactory.

4. In types such as 1–b, 2–b, 3–b, and 4–b in both figures 53 and 54 it is desirable but not essential that the edge joints come under the end fittings.

5. The edge joints as shown in types 1–b, 2–b, 3–b, and 4–b in figures 53 and 54 should be staggered, preferably about 1 inch.

6. The taping of built-up struts hides the glued surfaces from inspection and, as it does not add to the strength, seems unnecessary.

7. The use of waterproof glue for built-up struts is recommended.

8. There is reason to believe that the construction of solid and routed built-up struts can be improved over present practice and over that here shown so as to more effectively relieve the internal stresses which tend to produce warping. It should be remembered, therefore, that while the information here presented is based on the most complete data now available on built-up struts the subject is one which has been but little studied and great improvements may consequently be expected.

Figure 55 shows various types of strut construction which have been used in machines or proposed for use.

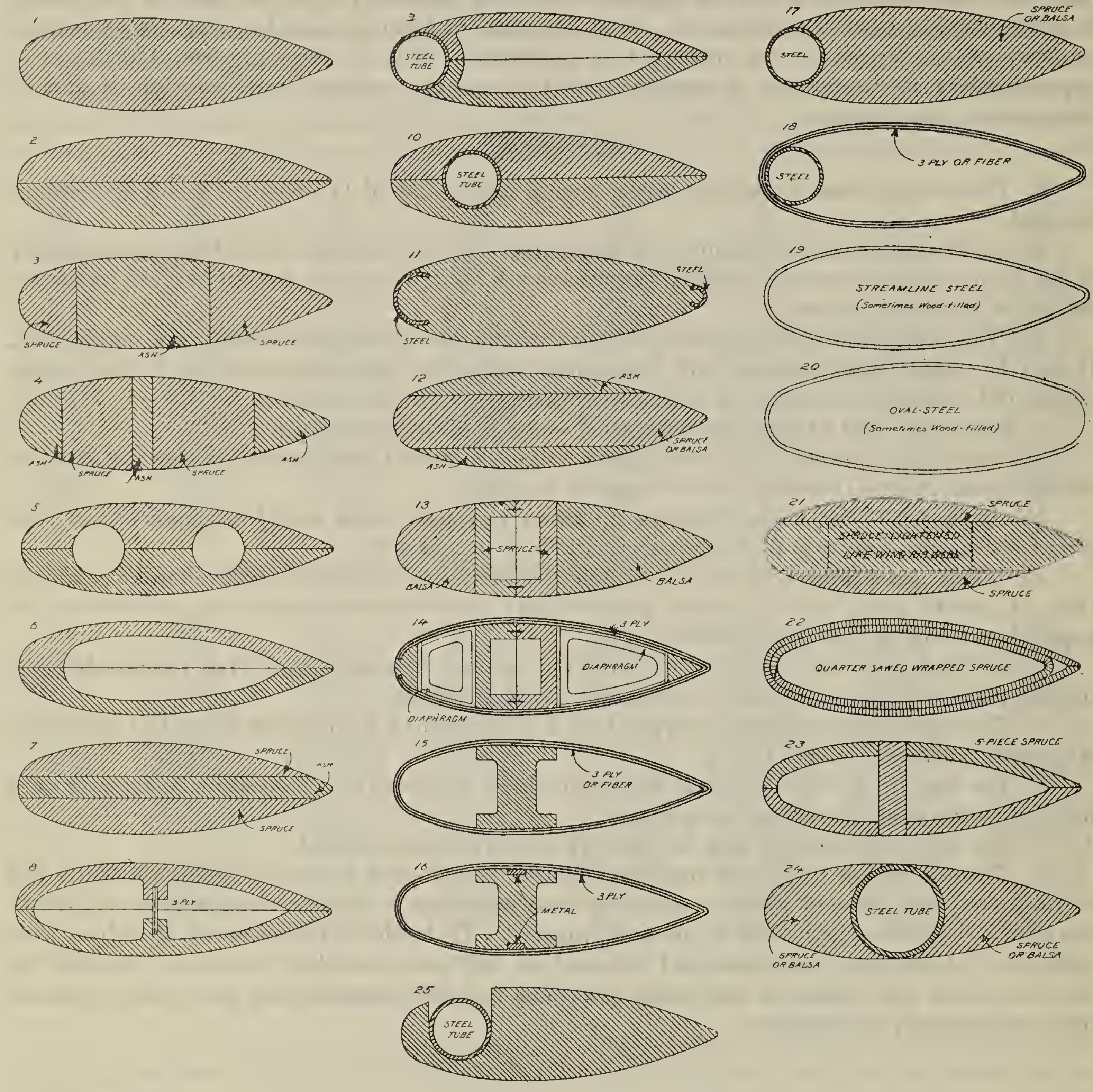

Fig. 55.—Typical built-up strut sections.

WING RIBS.

The construction and loading of wing ribs is of such a nature that it is practically impossible to calculate, with any reasonable degree of accuracy, the actual strength of any particular design. Further, it is quite impossible to determine without actual test the relative efficiency and strength of the various elements of the rib. As a result of these conditions it has been found necessary to develop a number of types through test. Some of the types which have been used or proposed for use are shown in figure 56. A number of these types have been tested, and several of them were developed as a result of the experiments.

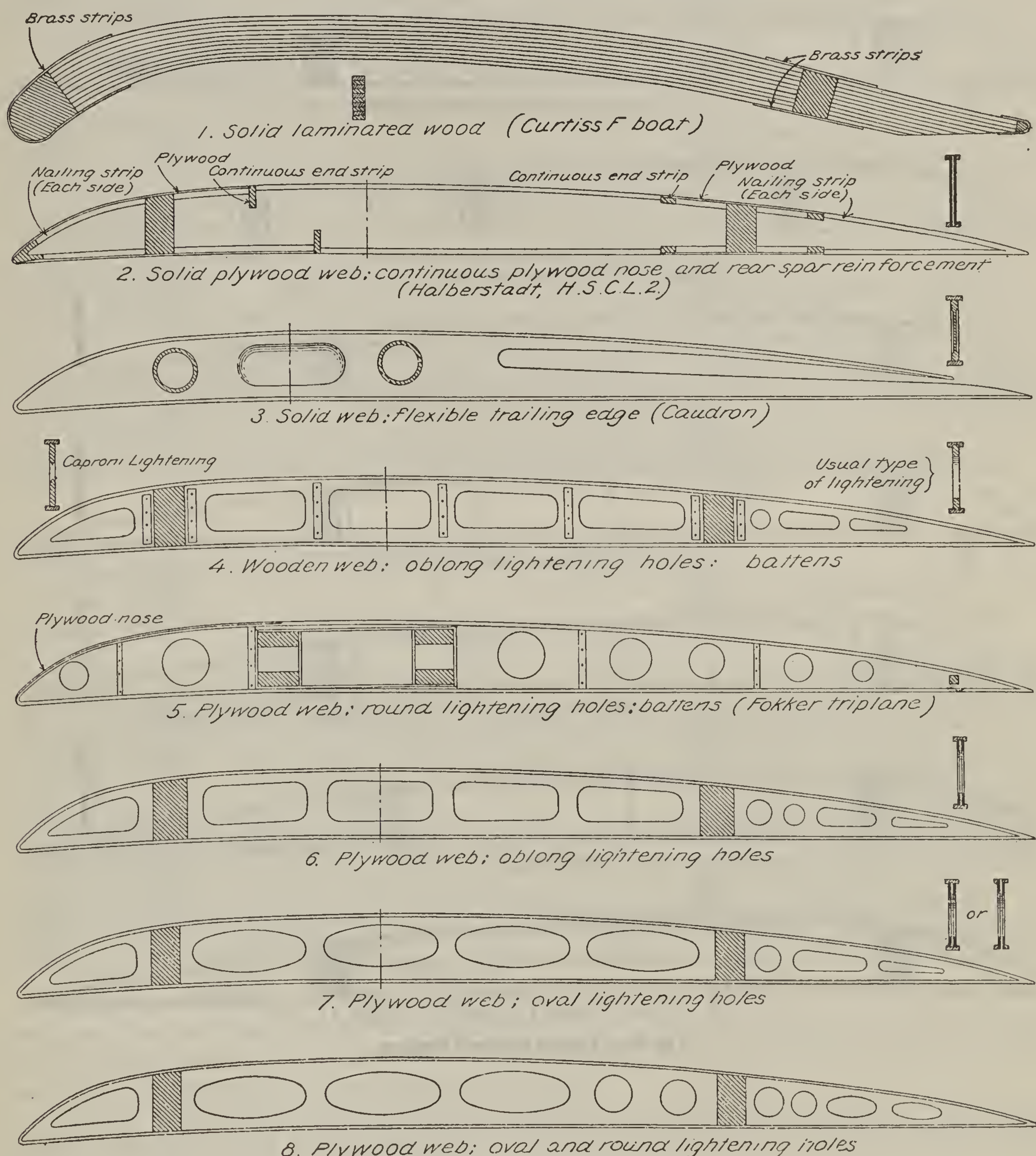

Fig. 56.—Typical wing-rib designs.

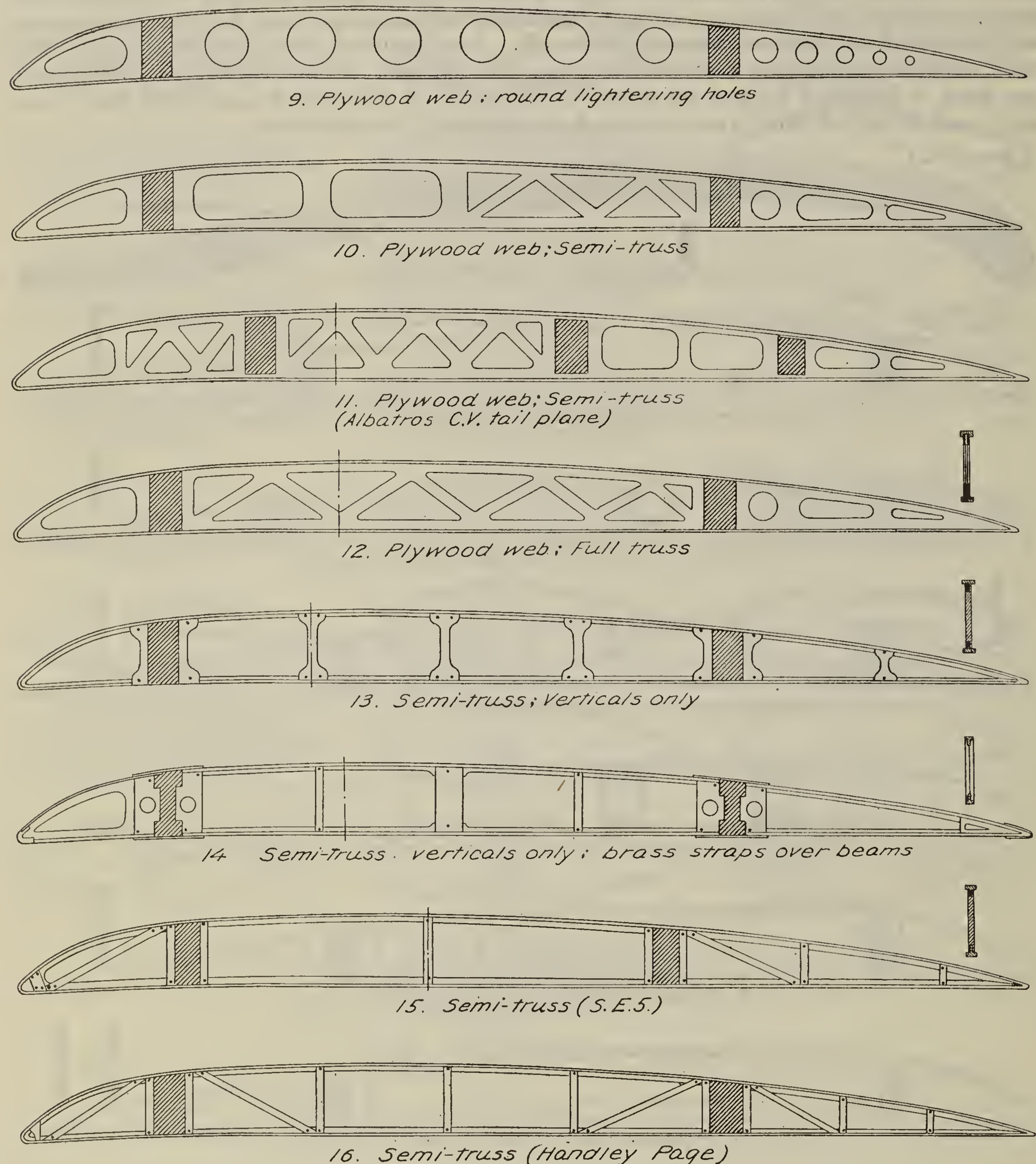

Fig. 56.—Typical wing-rib designs.

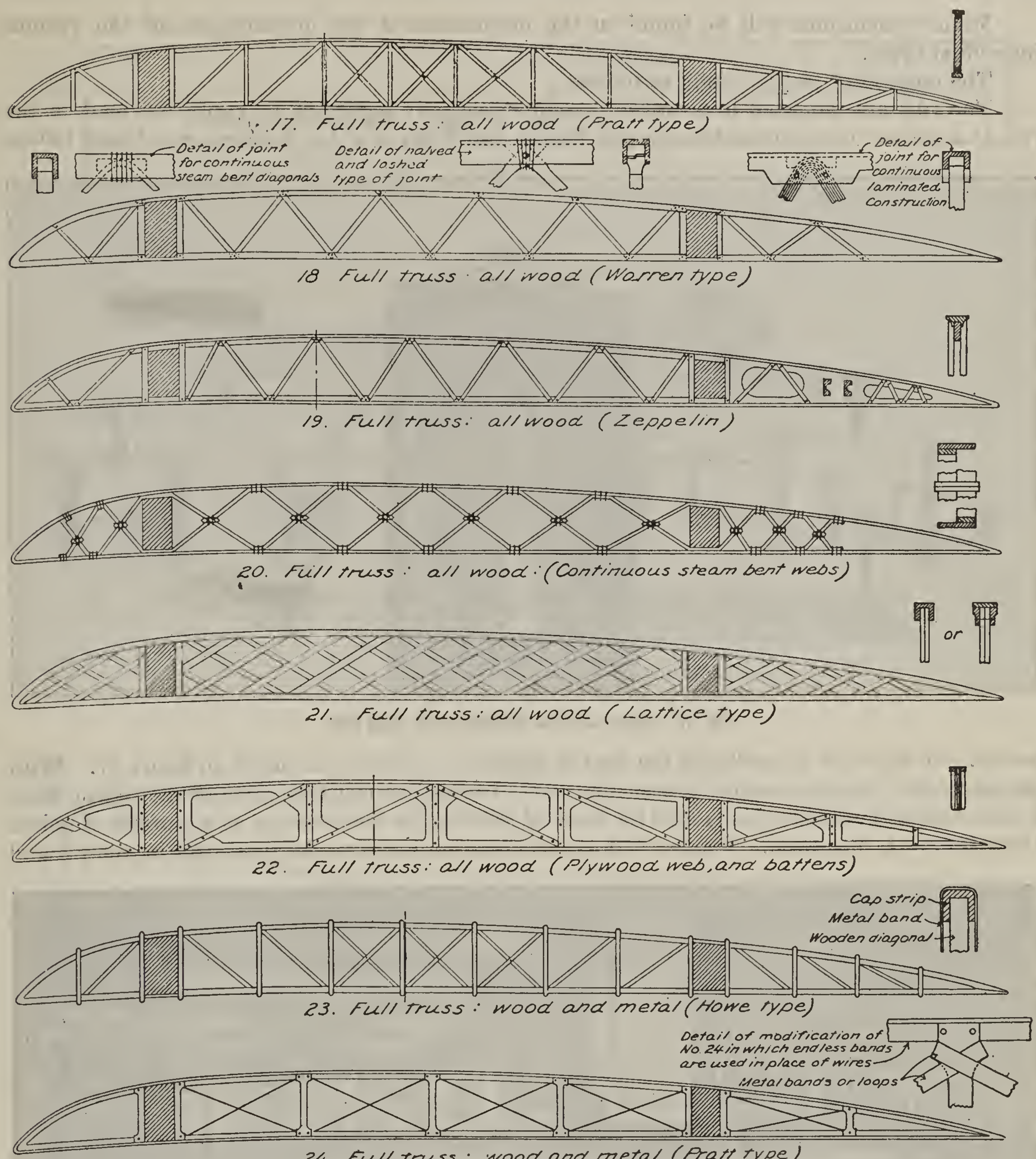

Fig. 56.—Typical wing-rib designs.

The two outstanding conclusions from the tests are: (1) The type of rib most suitable for small and medium chords, from the standpoint of the strength weight ratio combined with manufacturing ease, is the plywood web type, with oval and circular openings (fig. 56, case 8) and with vertical grain in the outer plies of the web.

(2) The type of rib most suitable for large chords is the full truss type. This has the greatest strength-weight ratio of all types, and the manufacturing difficulties are not overwhelmingly large in the case of large ribs.

Minor conclusions will be found in the discussions of the development of the various individual types.

The method of test is briefly as follows:

The ribs are mounted in a testing machine specially equipped to apply the load to the ribs at a number of points and the testing head is run down at a slow uniform speed until failure

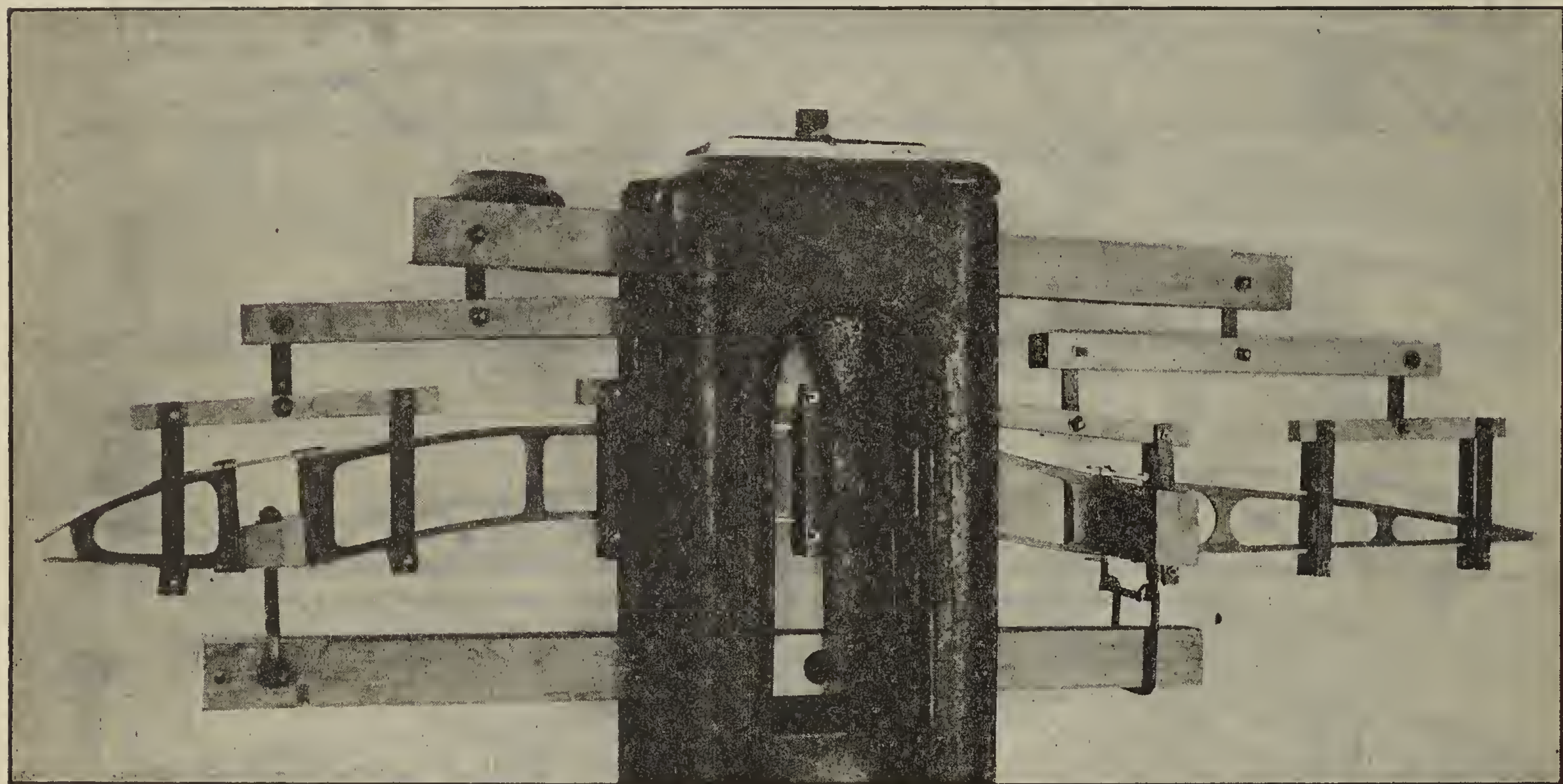

Fig. 57.—Apparatus for testing small wing ribs.

occurs. In the case of small ribs the load is applied at 8 points, as shown in figure 57. With the larger ribs 16-point loading is used (fig. 58). During the test the travel of the testing head is recorded at the various loads, and for some of the ribs the deformation at a number of points along the rib is measured. Figure 59 shows the relation between the total load in pounds and

Fig. 58.—Apparatus for testing large wing ribs.

the travel of the testing head in inches. The strengthening and stiffening accomplished by judicious reinforcement are clearly shown.

The load distribution used in the first series of tests is shown in figure 60. Later a triangular distribution was adopted, in which the apex of the triangle is one-fourth of the chord from the leading edge (fig. 68).

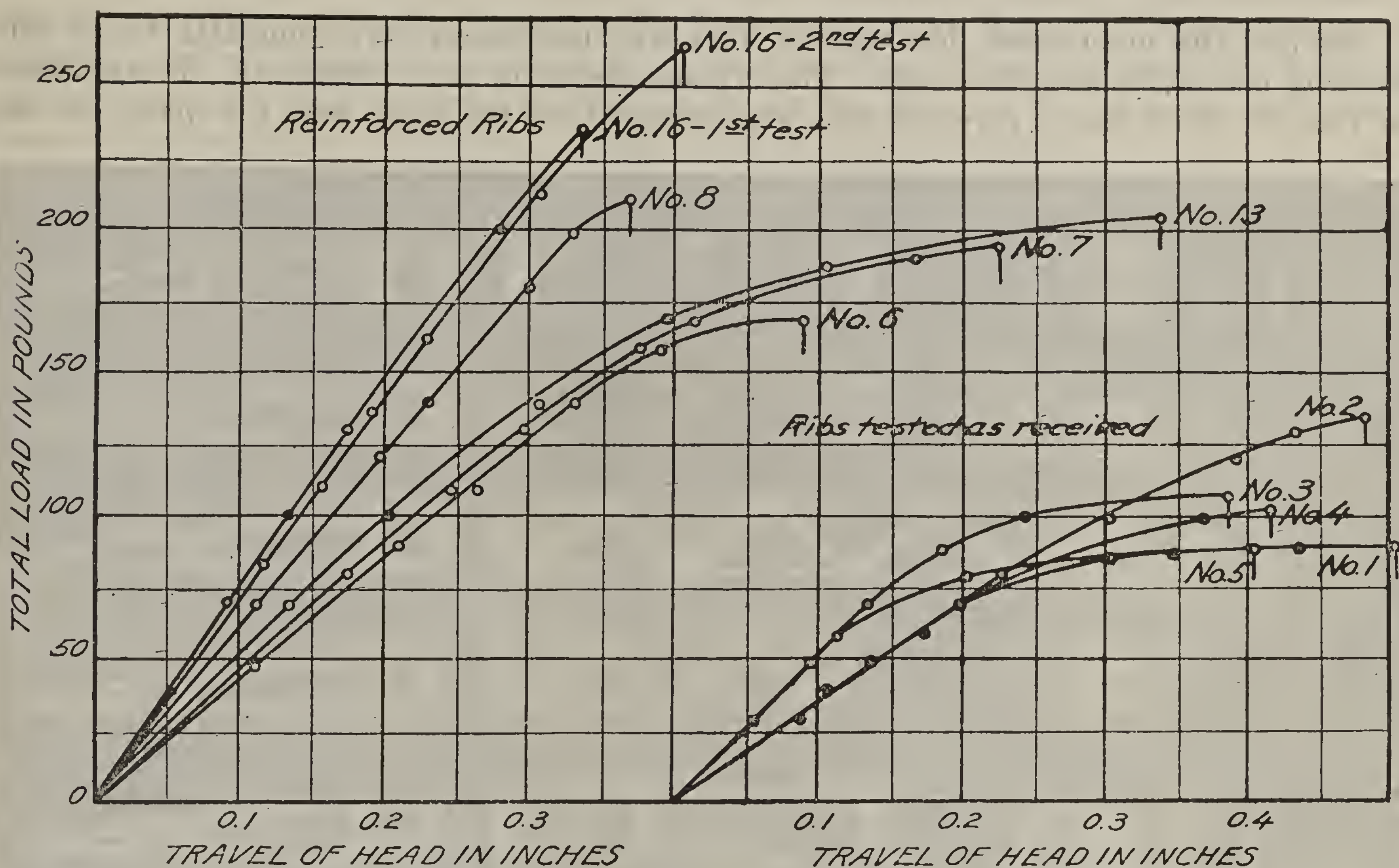

Fig. 59.—Wing rib load—deformation curves: DH-4 ribs.

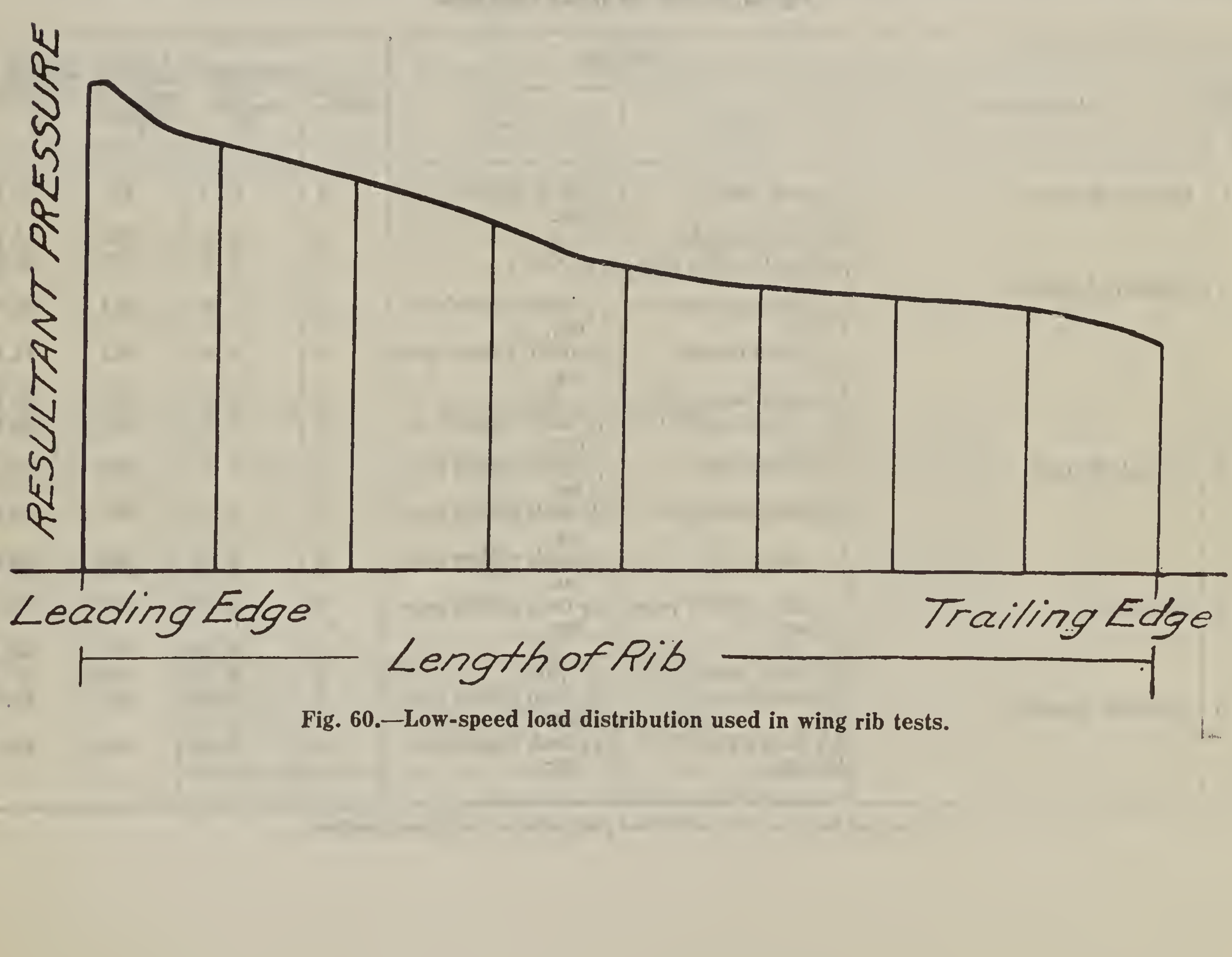

Fig. 60.—Low-speed load distribution used in wing rib tests.

TESTS ON DH-4 WING RIBS.

The first ribs upon which development work was undertaken were some DH-4 ribs submitted by one of the manufacturers. The original design is No. 1, figure 61. It was found that this rib, which has a plywood web, was lightened out too much near the spars, and the

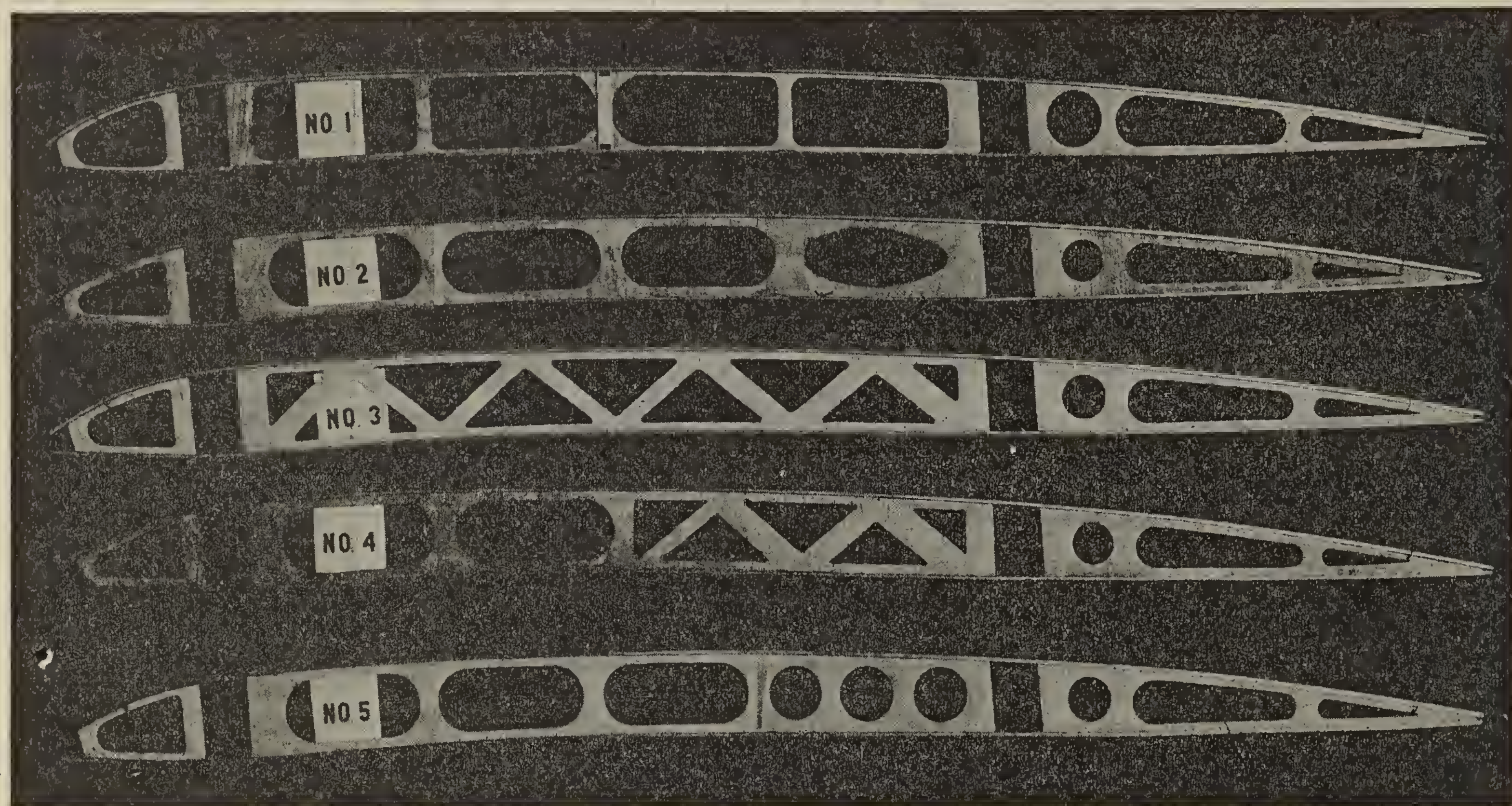

Fig. 61.—Tests on DH-4 wing ribs.

Rib. No.	Designation.	Description. Faces.	Description. Core.	Number of tests.	Net weight of rib, ounces, W.	Average total load sustained, pounds, P.	Ratio of strength to weight, $\frac{P}{W}$
1	Dayton-Wright	$\frac{1}{20}$-inch birch	$\frac{1}{16}$-inch yellow poplar.	4	7.71	136	17.7
2	Improved original	$\frac{1}{100}$-inch maple	do	2	5.23	232	44.4
		$\frac{1}{60}$-inch yellow poplar.	do	3	5.58	243	43.5
		$\frac{1}{64}$-inch Spanish cedar.	$\frac{1}{16}$-inch Spanish cedar.	3	5.26	274	52.1
3	Complete truss	$\frac{1}{100}$-inch maple	$\frac{1}{16}$-inch yellow poplar.	2	5.59	232	41.5
		$\frac{1}{40}$-inch basswood	do	3	5.85	243	41.5
		$\frac{1}{64}$-inch Spanish cedar.	$\frac{1}{16}$-inch Spanish cedar.	5	5.06	253	50.0
		$\frac{1}{70}$-inch birch	$\frac{1}{12}$-inch yellow poplar.	3	5.64	266	47.2
		$\frac{1}{40}$-inch basswood *	$\frac{1}{16}$-inch yellow poplar.	5	6.37	297	46.6
		do	$\frac{1}{12}$-inch yellow poplar.	4	6.12	300	49.0
4	Semitruss	$\frac{1}{60}$-inch yellow poplar.	$\frac{1}{16}$-inch yellow poplar.	4	5.46	274	50.2
5	Circular opening	do	do	3	5.20	288	55.4
		$\frac{1}{40}$-inch basswood	do	3	5.61	325	57.9
		$\frac{1}{70}$-inch birch	$\frac{1}{12}$-inch yellow poplar.	3	5.52	337	61.0
		$\frac{1}{40}$-inch Spanish cedar.	$\frac{1}{16}$-inch Spanish cedar.	2	5.40	346	64.0

* Core and face grain run parallel and perpendicular to diagonal members.

first improvement consisted in changing the shape and size of the lightening holes and incidentally reducing the weight by making the face veneer much lighter. The improvement in strength is shown in the last column of the table. Further development work led through the semitruss and full truss (plywood) designs to the design which was finally decided upon as the best obtainable (No. 5). This rib is shown drawn to scale in figure 62.

Several other types of DH–4 ribs were submitted for test, among them being several similar to case 13, figure 56. These were found to be very weak indeed, but stiffening and strengthening by means of wires, case 24, figure 56, produced a marked improvement. In fact, one rib developed as much as 42 pounds per ounce of weight.

Conclusions drawn from these tests, which included 150 ribs, are as follows:

(1) Plywood webs are superior to single-piece webs in strength, even if the latter are reinforced with vertical strips glued and nailed in position.

(2) Plywood webs with the face grain vertical are superior to plywood webs having the face grain longitudinal.

(3) Nails in the cap strips are practically useless in so far as contributing to the strength of the rib is concerned.

(4) Cap strips should be fastened rigidly to the spars.

(5) The circular-opening type of rib is superior to the other types tested.

(6) For the size of rib tested a core of one-sixteenth yellow poplar or Spanish cedar veneer with longitudinal grain is satisfactory. If high-density wood, like birch, is used for face veneer, the thickness should be from one-sixtieth to one-seventieth inch, while if low-density face veneer, such as yellow poplar, is to be used, a thickness of one-fortieth to one-fiftieth inch is required.

(7) Low-density face veneer is superior from the standpoint of manufacture of the plywood, and also gives somewhat greater stiffness for the same weight.

(8) Spruce cap strips $\frac{3}{16}$ by $\frac{7}{16}$ inch are satisfactory. They should be grooved and well glued.

TESTS ON SE–5 WING RIBS.

Table 17 presents the test data on a number of SE–5 ribs of the original design and of the design developed at the laboratory. The original ribs submitted for test were similar to case 15, figure 56, and consisted of 22 pieces. Under low-speed loading, figure 60, these ribs developed a strength of 25.3 pounds per ounce of weight, and under high-speed loading, figure 68, the average strength was 28.1 pounds per ounce of weight.

TABLE 17.—*Tests on SE–5 wing ribs.*

Rib number.	Type of rib.	Web construction.		Load distribution.	Net weight of rib, oz., W.	Total load sustained, lbs., P.	$\frac{P}{W}$
		Faces.	Core.				
Average of 1, 2, 6, 7	Original	Spruce braces and struts		Low speed	6.67	169	25.3
Average of 11, 12, 13, 14	do	do		High speed	6.59	185	28.1
Average of 3, 4, 5	Plywood No. 1	$\frac{1}{55}$-inch birch	$\frac{1}{16}$-inch basswood	Low speed	6.17	315	51.0
Average of 8, 9, 10	do	do	do	High speed	5.89	291	49.4
Average of 19, 20, 21, 22	Plywood No. 2	$\frac{1}{40}$-inch Spanish cedar.	$\frac{1}{16}$-inch Spanish cedar.	Low speed	4.61	270	58.5
Average of 15, 16, 17, 18	do	do	do	High speed	4.60	249	54.2
Average of 23, 24, 25, 26	do	do	do	Low speed	4.21	246	58.5
Average of 27, 28, 29, 30	do	do	do	High speed	4.23	275	65.0

Ribs No. 1 to 22, inclusive, loose in spars, bound by wire wound around rib at spars.
Ribs No. 23 to 30, inclusive, were glued to spars.
In all plywood web ribs the face grain was vertical.
Cap strips for ribs 1, 2, 6, 7, 11, 12, 13, and 14 were $\frac{3}{16}$ by $\frac{1}{2}$ inch spruce.
Cap strips for ribs 3, 4, 5, 8, 9, and 10 were $\frac{3}{16}$ by $\frac{7}{16}$ inch spruce.
Cap strips for ribs 15 to 30, inclusive, were $\frac{1}{4}$ by $\frac{7}{16}$ inch spruce.

The design finally developed is shown in detail in figure 63. Several types were made up, using different species and thicknesses of veneer in the web plywood. Of these the ribs having webs composed of one-fortieth-inch Spanish cedar faces and one-sixteenth-inch Spanish cedar core proved to be the strongest per unit of weight. The strength under low-speed loading was 58.5 pounds per ounce of weight, and under high-speed loading a strength of 65 pounds per ounce of weight was developed.

Besides being much stronger and lighter than the original ribs, the final design is decidedly stiffer.

TESTS ON HS WING RIBS.

The original HS ribs have a pine web, and are of the general type shown in case 4, figure 56. The final design is of the plywood web, oval and circular opening type, and is shown in detail in figure 64. Detailed results of the tests are presented in table 18. Attention is directed to the cap strips, which are patterned after the design used by Fokker in his recent biplane. Better cap-strip fastening is secured by this method when the web is thin. The basswood faces on the plywood web of the final design appear to be somewhat light, and it is anticipated that better results would be secured by the use of slightly heavier veneer.

TABLE 18.—*Tests on HS-1L wing ribs.*

Type of construction.	Load distribution.	Net weight of rib, ounces, W.	Total load sustained, pounds, P.	Ratio of strength to weight, $\frac{P}{W}$.	Remarks.
Present construction, single-ply pine web.	High speed....	16.80	410	....	$\frac{1}{4}$-inch, single-ply pine web; $\frac{1}{4}$ by $\frac{3}{4}$ inch spruce cap strips; 1 by $\frac{1}{16}$ inch stiffeners on each side of web between openings.
Do........................	.....do.........	17.28	440	....	
Do........................	.....do.........	16.31	350		
Average....................	.....do.........	16.80	400	24	
Present construction, single-ply pine web.	Low speed......	16.15	458	....	Construction same as above.
Do........................	.....do.........	16.31	530	....	
Do........................	.....do.........	16.80	590	....	
Average....................	.....do.........	16.42	526	32	
Circular opening, plywood web	High speed....	10.96	385	....	Ply-wood web; $\frac{1}{32}$-inch basswood faces; $\frac{1}{8}$-inch basswood core; $\frac{3}{16}$ by $\frac{1}{4}$ inch spruce cap strip on each side of web; grain of faces of web vertical.
Do........................	.....do.........	10.81	365	....	
Do........................	.....do.........	10.81	310	....	
Average....................	.....do.........	10.86	353	32	
Circular opening, plywood web	Low speed.....	10.68	490	....	Construction same as above.
Do........................	.....do.........	10.75	600	....	
Do........................	.....do.........	10.90	500	....	
Average....................	.....do.........	10.78	530	49	

TESTS ON F5-L WING RIBS.

The original F5-L ribs were of the general type of the HS ribs, case 4, figure 56. In developing the new ribs, it was thought that the use of a full truss type rib might be justified and, therefore, a rib of this type was designed and tested. Further, a truss type with plywood web was included in the series. The three designs are shown in figures 65, 66, and 67, and the results of the tests upon the three types with high-speed loading and low-speed loading are shown in table 19. Data on the strength of the original design are also included.

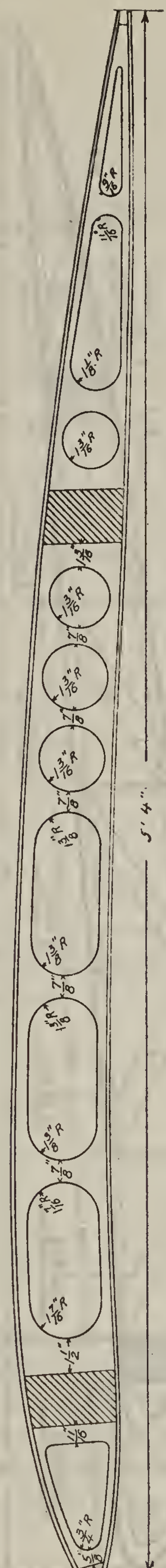

Fig. 62.—Circular opening type wing rib for DH-4 machine.

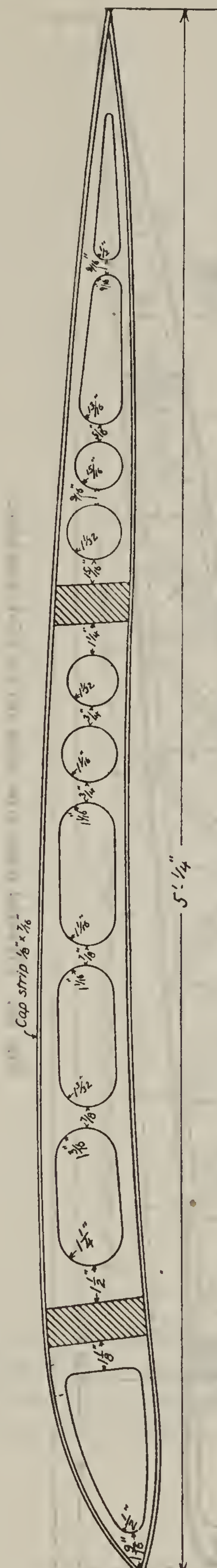

Fig. 63.—Circular opening type wing rib for SE-5 machine.

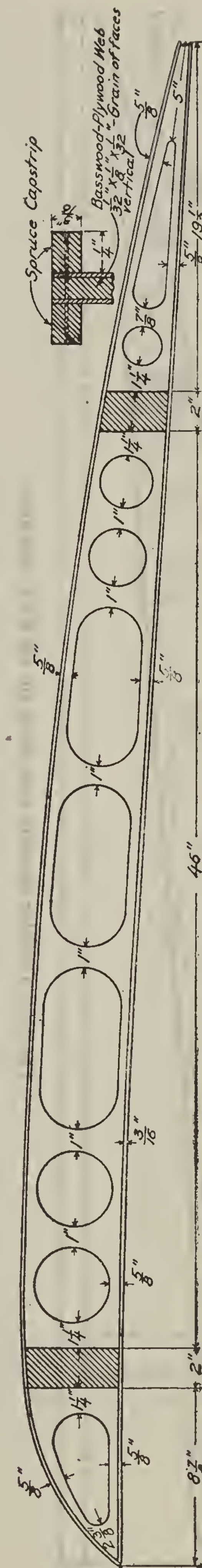

Fig. 64.—Circular opening type wing rib for HS-1L machine.

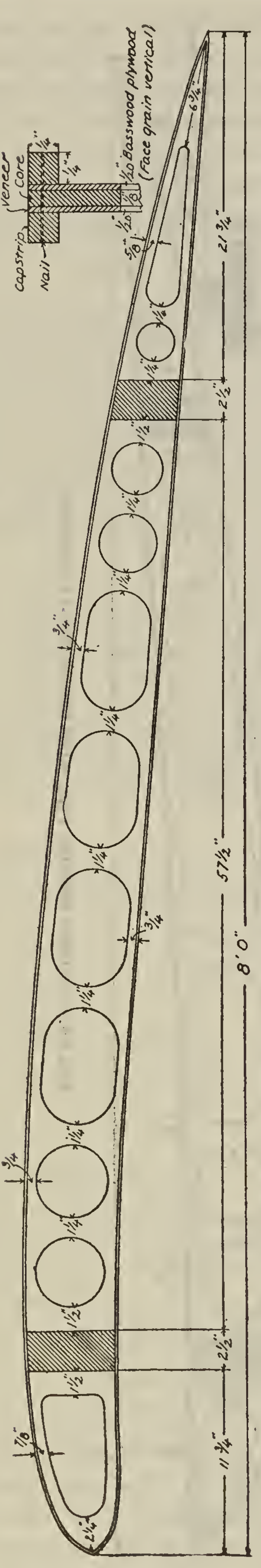

Fig. 65.—Circular opening type wing rib for F5-L machine.

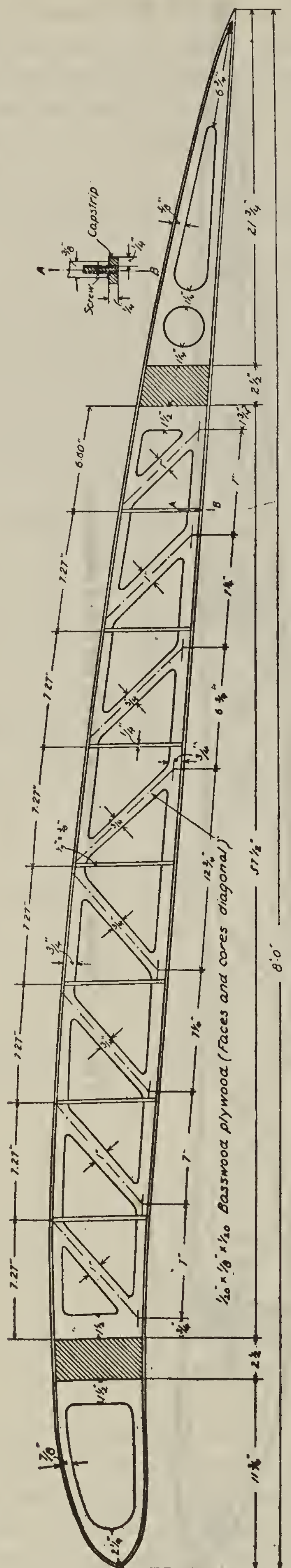

Fig. 66.—Plywood truss type wing rib for F5-L machine.

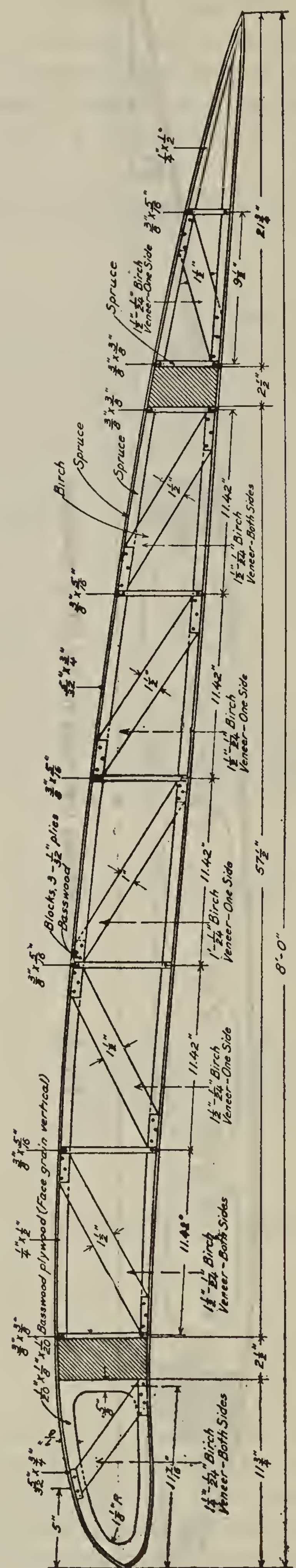

Fig. 67.—Pratt truss type wing rib for F5-L machine.

TABLE 19.—*Tests of F5-L wing ribs.*

No.	Design of rib.	Load distribution.	Net weight of rib, ounces. W.	Total load sustained, pounds. P.	Ratio of strength to Weight. $\frac{P}{W}$
1	Plywood, circular opening	High speed	15.5	540	
2	.....do	.....do	15.5	485	
3	.....do	.....do	15.7	400	
	Average 1, 2, and 3		15.6	475	31
4	Plywood, circular opening	Low speed	15.5	592	
5	.....do	.....do	15.7	498	
6	.....do	.....do	15.5	642	
	Average 4, 5, and 6		15.6	577	37
7	Plywood, truss	High speed	22.4	508	
8	.....do	.....do	23.4	533	
9	.....do	.....do	26.4	670	
	Average 7, 8, and 9		24.0	570	23.7
10	Plywood, truss	Low speed	23.0	610	
11	.....do	.....do	23.8	578	
12	.....do	.....do	23.0	683	
	Average 10, 11, and 12		23.3	624	26.7
13	Truss	High speed	12.5	580	
14	.....do	.....do	12.5	505	
15	.....do	.....do	12.3	520	
	Average 13, 14, and 15		12.4	535	43
16	Truss	Low speed	12.5	665	
17	.....do	.....do	12.9	710	
18	.....do	.....do	12.6	610	
	Average 16, 17, and 18		12.7	662	52
19	Original design	High speed	22.1	485	
20	.....do	.....do	22.1	405	
21	.....do	.....do	21.0	400	
22	.....do	.....do	21.8	435	
	Average 19, 20, 21, and 22		21.7	431	20
23	Original design	Low speed	22.8	593	
24	.....do	.....do	23.4	585	
25	.....do	.....do	23.5	550	
26	.....do	.....do	24.2	590	
	Average, 23, 24, 25, and 26		23.5	579	25

It will be seen from the data presented that the full truss type, figure 67, developed very much greater strength per unit weight than either of the other types and that the plywood truss type, figure 66, was by far the weakest of the three. Final choice between the full truss type and the plywood web type must be determined by the relative importance of weight saving and cost of production.

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TESTS ON 15-FOOT WING RIBS.

The largest ribs so far tested have a 15-foot chord and were designed for a machine under contemplation but not yet built. Three general types of rib were first tested, a plywood web circular opening type, a semitruss type with reinforced plywood web, and a full truss type with vertical compression members and diagonal tension members (Pratt type). A glance at table 20 shows that the full truss was far superior to the other types in strength-weight ratio. The low-speed load distribution used is shown in figure 60 and the high-speed distribution in figure 68. The full truss design is shown in detail in figure 69. The stiffness of this design is illustrated in figure 70, which shows the relation between the travel of the testing head and the toal load in pounds. The uniformity in the properties of the three ribs is noteworthy. The need for thorough fastening of the cap strips and the verticals to the spars is emphasized.

Table 20.—*Tests on 15-foot wing ribs.*

No. of rib.	Type of rib.	Species of web.		Load distribution.	Cap strips.	Net weight of rib, pounds, W.	Total load sustained, pounds, P.	$\frac{P}{W}$ W= Weight in ounces.
		Faces.	Core.					
1	Circular opening	$\frac{1}{32}$-inch birch	$\frac{1}{16}$-inch Spanish cedar.	Low speed	$\frac{1}{4}$ by $\frac{3}{4}$ inch spruce.	2.42	251	6.5
2	do	$\frac{1}{45}$-inch birch	do	do	do	2.28	318	8.7
	Average values					2.35	285	7.6
7	Semitruss	$\frac{1}{30}$-inch birch	$\frac{1}{16}$-inch Spanish cedar.	High speed	$\frac{1}{4}$ by $\frac{3}{4}$ inch spruce.	2.92	286	6.1
8	do	$\frac{1}{45}$-inch birch	do	do	do	2.68	175	4.1
	Average values					2.80	231	5.1
10	Truss	Spruce compression members and web.		High speed	$\frac{3}{16}$ by $\frac{7}{8}$ inch spruce.	2.49	565	14.2
9	do	do		do	do	2.41	672	17.4
11	do	do		do	do	2.42	710	18.3
12	do	do		do	do	2.48	707	17.8
13	do	do		do	do	2.49	721	18.1
14	do	do		do	do	2.44	690	17.7
	Average values*					2.45	700	17.9

* (Rib No. 10 culled and omitted.)

After this series of tests was completed it was thought desirable to develop a truss type of rib which did not depend so largely upon glue for the security of the fastenings, and so a rib of the Warren type was designed and three built and tested. The design is shown in figure 71 and table 21 presents the results of the tests and also the results of the previous tests on the Pratt type for comparison. While the objects aimed at were attained, it was at the sacrifice of considerable weight, as will be seen from an inspection of the table. Tests have just been completed upon a number of modified ribs of the Warren type. These ribs showed a greater strength-weight ratio than any other 15-foot ribs tested at the laboratory.

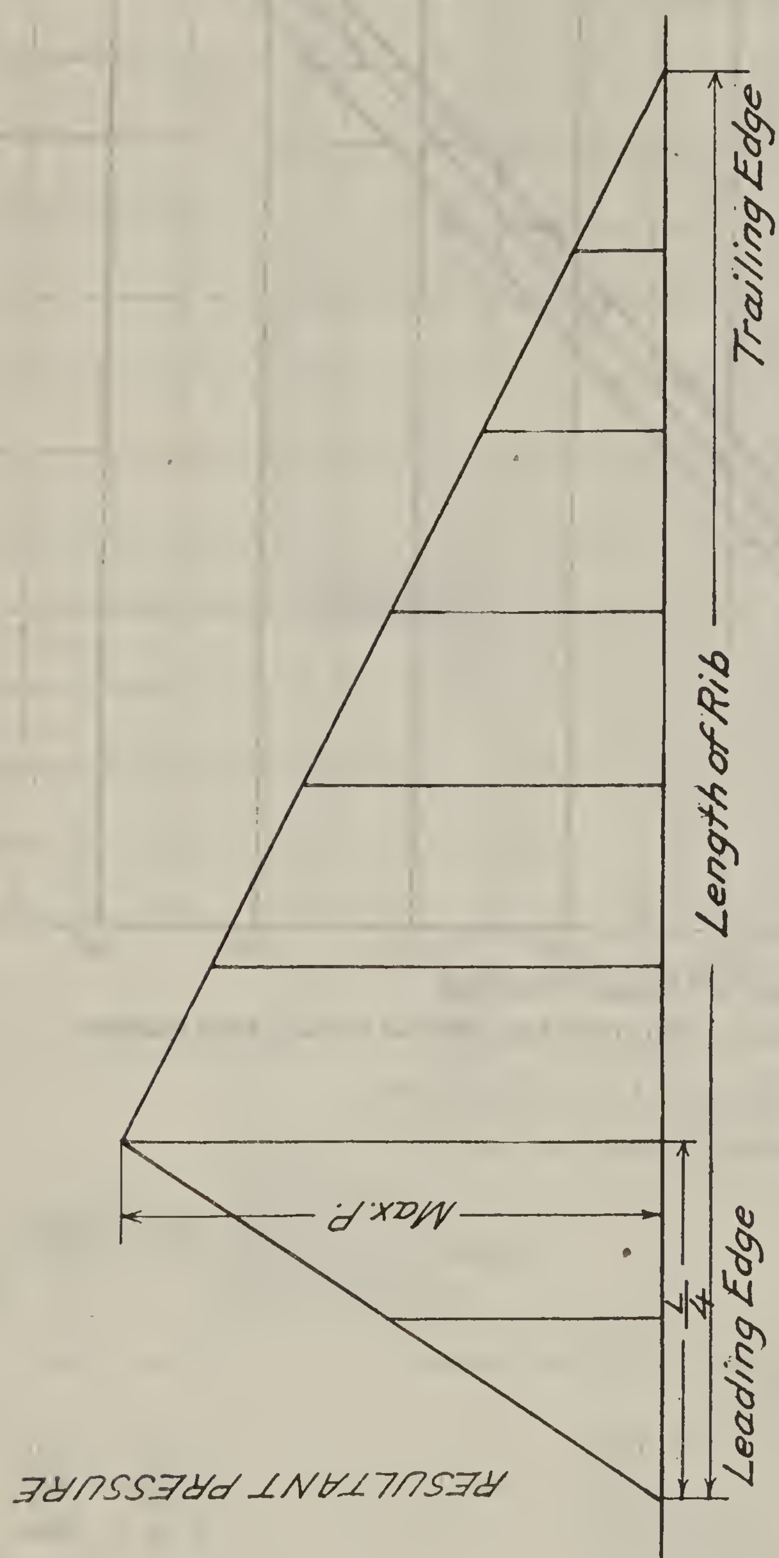

Fig. 68.—High-speed load distribution used in wing rib tests.

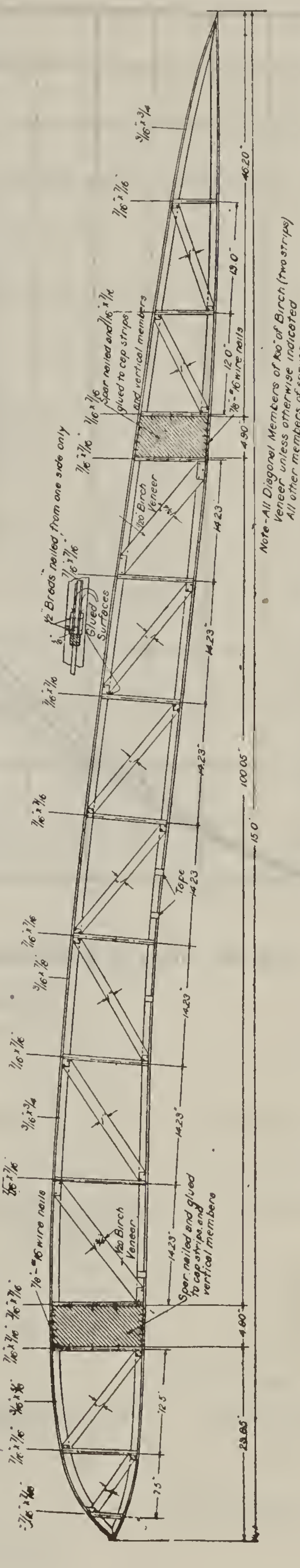

Fig. 69.—Pratt truss type wing rib for 15-foot chord. Modified R. A. F. 15 aerofoil.

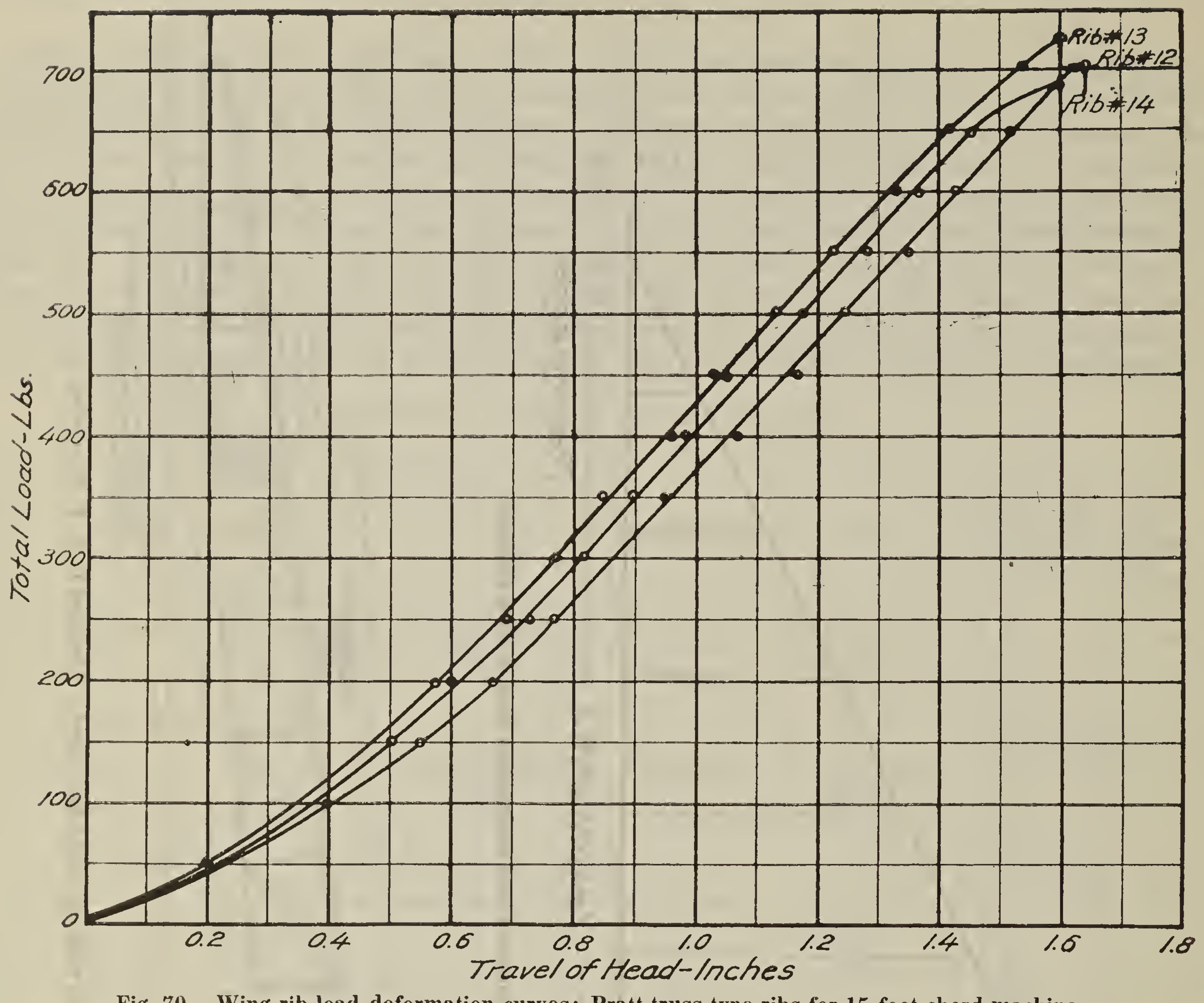

Fig. 70.—Wing rib load-deformation curves: Pratt truss type ribs for 15-foot chord machine.

TABLE 21.—*Tests on 15-foot wing ribs.*

Pratt truss and Warren truss type.

No. of rib.	Type of rib.	Construction.	Cap strips.	Net weight of rib pounds, W.	Total load sustained, pounds, P.	$\frac{P}{W}$ W=weight in ounces.
9	Pratt truss........	Spruce compression members and birch veneer tension members.	$\frac{3}{16}$ by $\frac{7}{8}$ inch spruce...........	2.41	672	17.4
11	.....do...........	.....do....................	.....do.....................	2.42	710	18.3
12	.....do...........	.....do....................	.....do.....................	2.48	707	17.8
13	.....do...........	.....do....................	.....do.....................	2.49	721	18.1
14	.....do...........	.....do....................	.....do.....................	2.44	690	17.7
	Average values..			2.45	700	17.9
15	Warren truss......	Plywood members............	Spruce channel, see sketch....	3.72	770	12.9
16	.....do...........	.....do....................	.....do.....................	3.54	855	15.1
17	.....do...........	.....do....................	.....do.....................	3.63	830	14.3
	Average values..			3.63	850	14.1

Ribs tested with high speed load distribution.

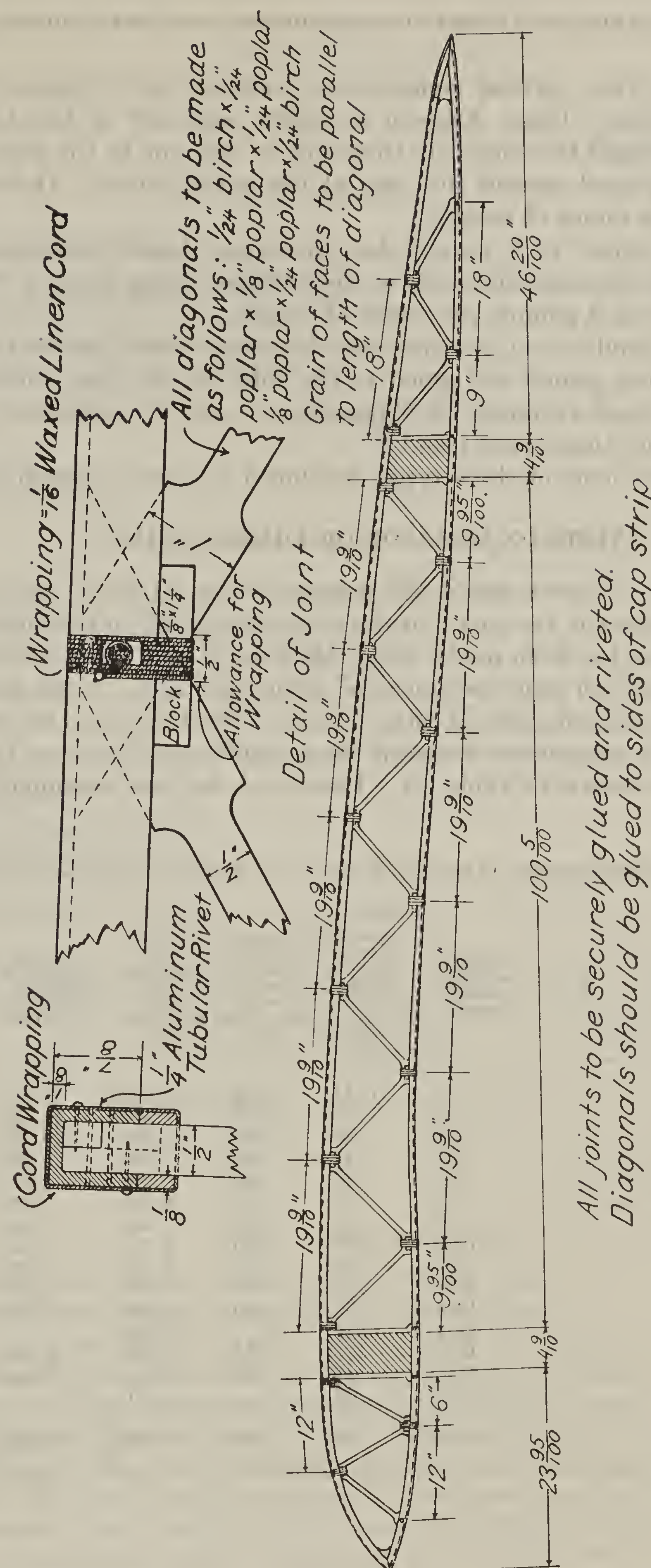

Fig. 71.—Warren truss type wing rib for 15-foot chord machine.

In addition to these types of 15-foot rib experiments were made upon three other types, as follows:

1. Full truss type, with vertical compression members and diagonal tension members running in both directions. These diagonal members consisted of two birch veneer bands wrapped continuously around the whole rib from end to end, one to the right and the other to the left. These bands passed around the caps at the panel points. These ribs developed a strength of 13 pounds per ounce of weight.

2. Full truss type, similar to 1, except that the veneer bands, instead of passing around the caps, passed between the caps and ends of the verticals, being given a twist at this point. The strength developed was 9 pounds per ounce of weight.

3. Full truss type, similar to 1, except that the veneer bands, instead of passing around the caps, were cut at these points and glued to the sides of the caps, which were of channel section. This type developed a strength of 13 pounds per ounce of weight and has the advantage of greater ease of assembly than types 1 and 2.

It is to be noted that none of these types developed as great strength as either the Pratt or Warren types.

TESTS ON ELEVATOR OR AILERON SPARS.

Comparatively little is known about the behavior of wood under torsion. This has not been of particular importance in the past, but the proper design of control surface spars demands such knowledge. Mention has been made, under Mechanical and Physical Properties of Wood, of a few torsion tests made on solid specimens of spruce and ash. A few tests have also been made on hollow dummy control spars of Sitka spruce. The individual results of the tests are given in table 22, and a comparison between these results and those on the solid specimens previously mentioned is shown in table 23. Details of the test specimens will be found in figure 72.

TABLE 22.—*Individual results of torsion tests on 15 hollow Sitka spruce elevator spars.*

Specimen No.	Moisture, per cent of oven-dry weight	Specific gravity (oven-dry weight and oven-dry volume).	Shearing stress at elastic limit (pounds per square inch).	Shearing stress at maximum load (pounds per square inch).	Shearing modulus of elasticity (pounds per square inch).	Work to elastic limit (inch pounds per cubic inch).	Work to maximum load (inch pounds per cubic inch).
1	12.6	0.44	500	1,000	92,100	1.12	7.1
2	15.0	.48	820	1,370	83,300	3.38	15.5
3	13.5	.38	950	1,000	79,500	4.75	6.4
4	12.8	.48	610	780	88,900	1.72	....
5	15.0	.45	930	1,260	76,100	4.74	11.4
6	14.2	.51	820	1,170	77,700	3.62	10.5
7	14.6	.34	710	940	55,300	3.84	9.1
8	13.2	.43	910	1,270	75,900	4.54	13.8
9	14.8	.50	820	1,070	77,800	3.62	8.0
10	13.6	.47	820	1,030	83,400	3.38	6.9
11	12.0	.52	740	1,040	73,800	3.06	7.3
13	13.4	.48	....	1,400	....	....	....
14	15.2	.37	910	1,350	80,600	4.27	15.8
15	13.4	.43	840	1,080	71,900	4.13	9.5
16	14.3	.49	....	970	....	....	....
Average	13.8	.455	800	1,110	78,200	3.55	10.11

TABLE 23.—*Summary of results of torsion tests on hollow Sitka spruce elevator spars and tests on solid circular specimens.*

	Tests on 15 hollow elevator spars, Sitka spruce (1).	Tests on 15 solid circular specimens Sitka spruce, (2).	Ratio of (1) to (2) in per cent.
Moisture, per cent of oven-dry weight	13.8	15.7	88
Specific gravity, based on oven-dry weight and oven-dry volume	0.46	0.39	118
Shearing stress at elastic limit (pounds per square inch)	[1] 800	1,090	73
Shearing stress at maximum load (pounds per square inch)	1,110	1,650	67
Shearing modulus of elasticity (pounds per square inch)	[1] 78,200	72,300	108
Work to elastic limit (inch pounds per cubic inch)	[1] 3.6	4.4	82
Work to maximum load (inch pounds per cubic inch)	[1] 10.1	19.7	51

[1] Based on 13 tests.

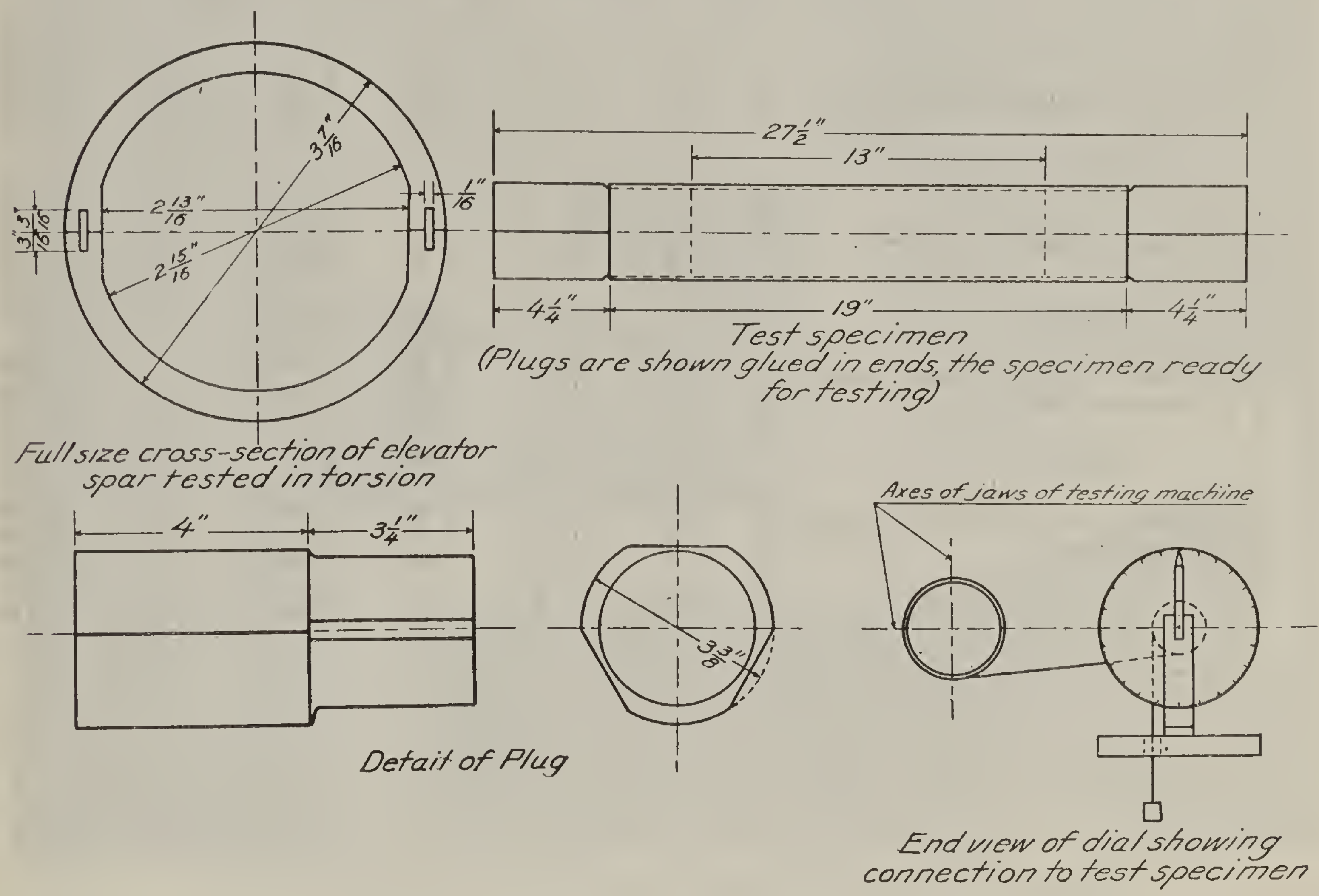

Fig. 72.—Torsion test specimen.

It is to be noted that 80 per cent of the specimens failed at or near the spline joint, indicating that the joint was a source of weakness in the specimens.

The relation between specific gravity and strength in shear is not definite enough to be used as a basis for selection of material to withstand shearing stresses.

These tests, as well as torsion tests in general, are subject to large variations. These variations are probably more pronounced in hollow spliced construction and will therefore necessitate using very large safety factors in order to obtain safe working stresses.

In addition to the tests already mentioned, a few tests have been made upon hollow spars with a hollow wooden core, around which veneer is wrapped in right and left spirals. The indications are that both the ultimate strength in torsion and torsional stiffness can be doubled by this method of construction.

TESTS ON AIRCRAFT ENGINE BEARERS.

A short series of tests was made to determine the relative merits of engine bearers built of all veneer and those built with a spruce filler. A preliminary series indicated the desirability of making a few modifications in the arrangement of the material which were embodied in the bearers here reported. The details of the veneer and spruce filler types are shown in figures 75 and 76, respectively, and the methods used in thrust loading and in vertical loading are illustrated in figures 73 and 74, respectively. The results of the tests are shown in table 24:

TABLE 24.—*Tests on modified engine bearers (second series).*

Engine bearers No.	Type.	Weight, pounds.	Moisture content at test.	Deflection at maximum thrust load, in inches.	Maximum thrust load, in pounds.	Deformation at maximum vertical load, in inches.	Maximum vertical load, in pounds.
1	All-veneer (grain of faces horizontal)	6.88	13.0	2.81	1,430	0.63	11,560
2		7.27	13.4	1.75	1,360	.61	12,260
3		7.30	13.2	2.25	1,580	.49	11,800
	Average	7.15	13.2	2.27	1,457	.58	11,873
4	All-veneer (grain of faces vertical)	7.54	12.8	2.12	1,940	.40	11,360
5		7.11	11.8	2.42	1,850	.56	11,540
6		7.40	13.6	1.65	2,000	.45	10,500
	Average	7.35	12.7	2.06	1,930	.47	11,133
7	Plywood with spruce filler (grain of faces horizontal).	7.10	12.3	2.04	1,850	.38	12,500
8		7.14	12.5	1.82	1,720	.48	17,000
9		7.26	12.2	1.84	1,690	.50	16,000
	Average	7.17	12.3	1.90	1,753	.45	15,167
10	Plywood with spruce filler (grain of faces vertical).	7.12	11.6	1.88	1,960	.60	16,500
11		7.20	11.7	1.62	1,910	.49	16,500
12		7.02	12.1	2.45	2,150	.67	15,430
	Average	7.11	11.8	1.98	2,007	.59	16,143

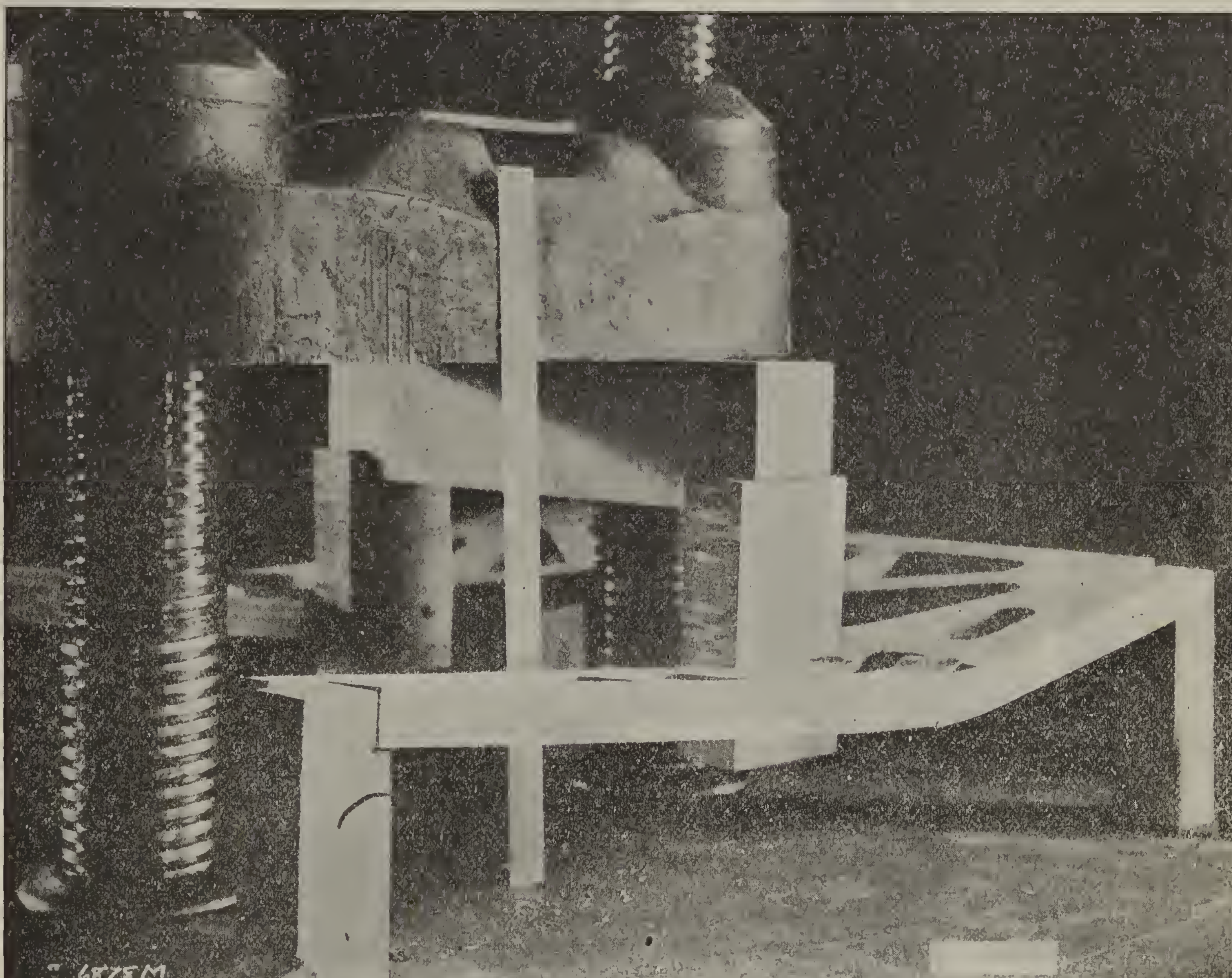

Fig. 73.—Strength tests of engine bearers: Method of testing for thrust loading.

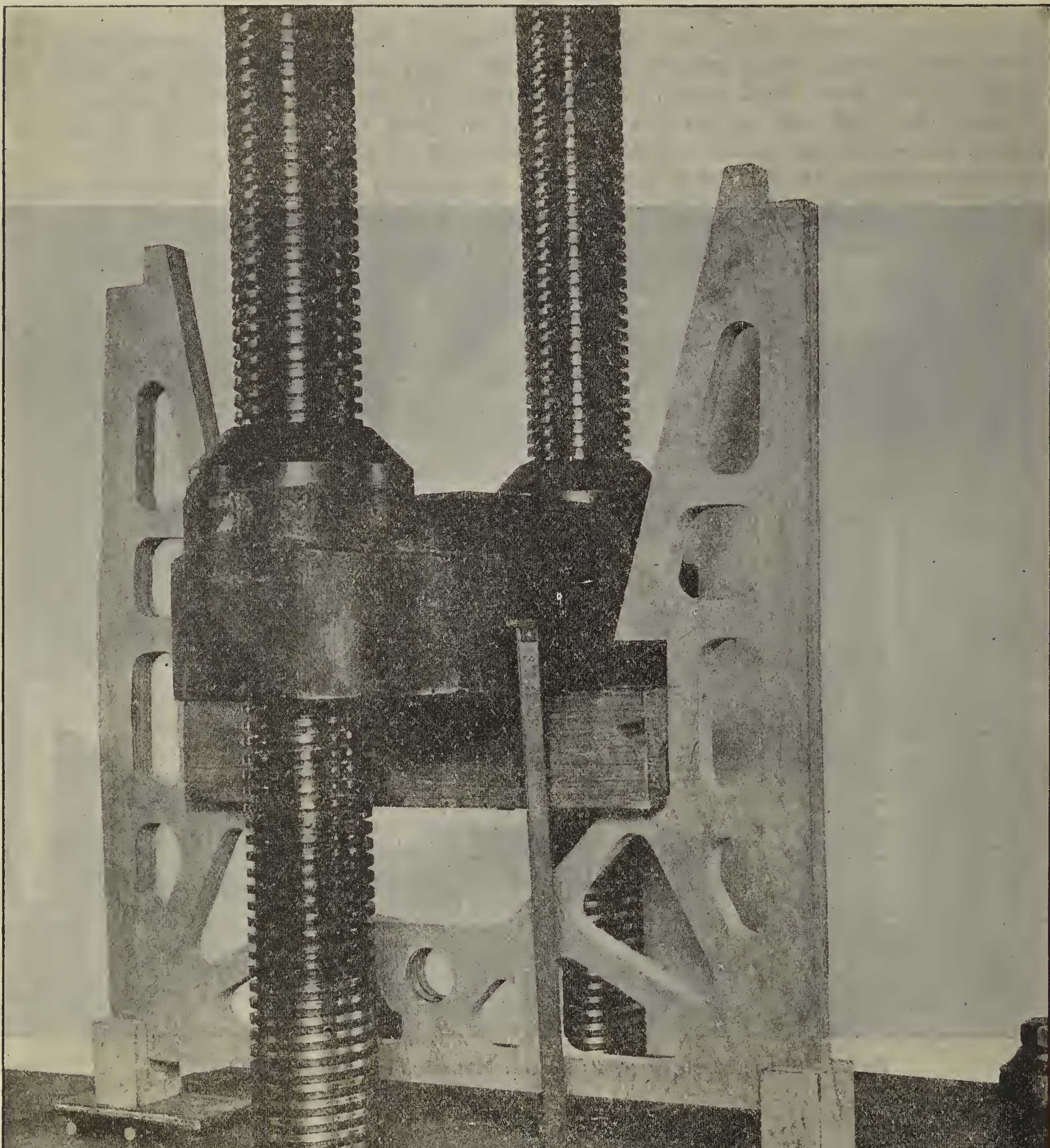

Fig. 74.—Strength tests of engine bearers: Method of testing for vertical loading.

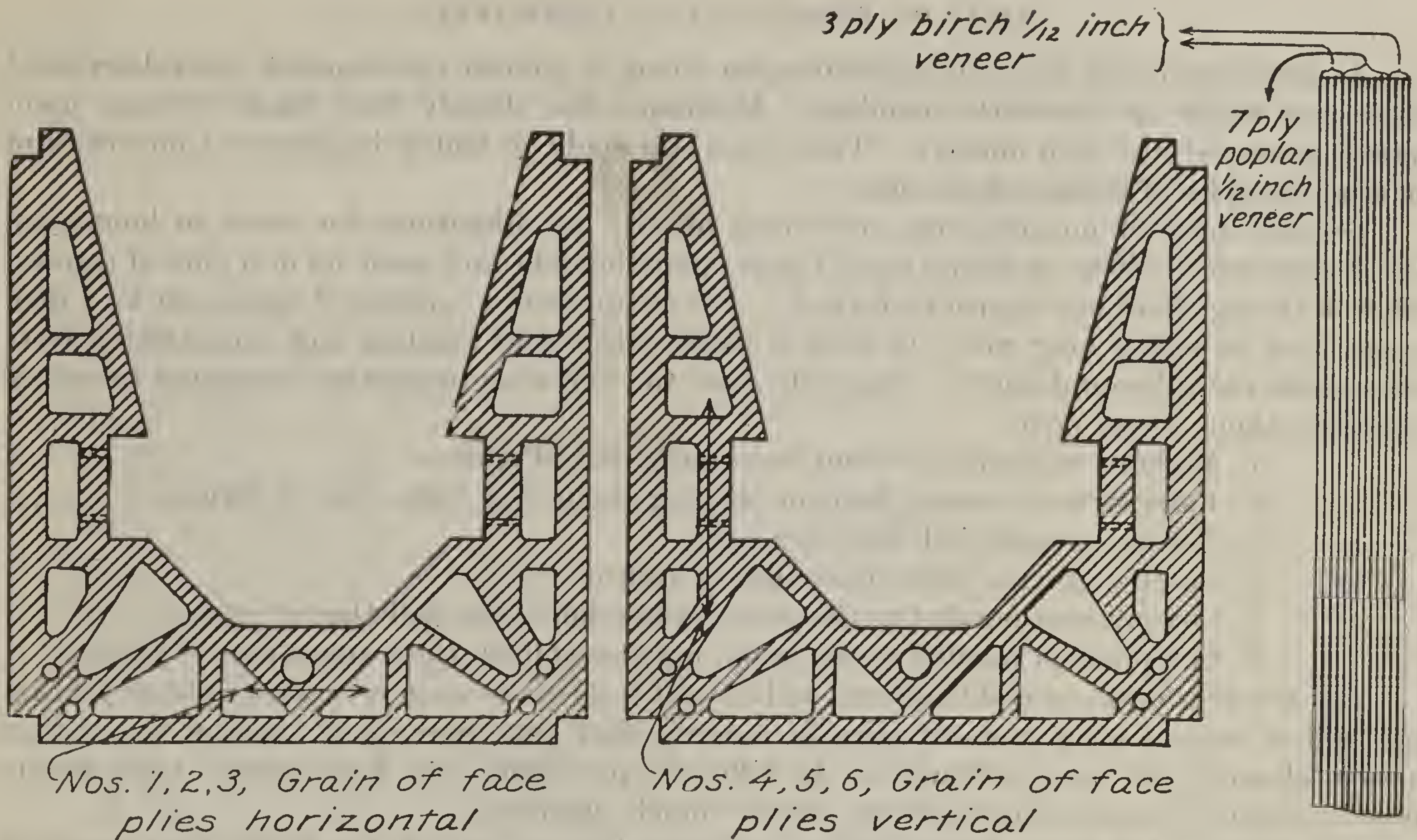

Fig. 75.—Engine bearers, all-veneer type.

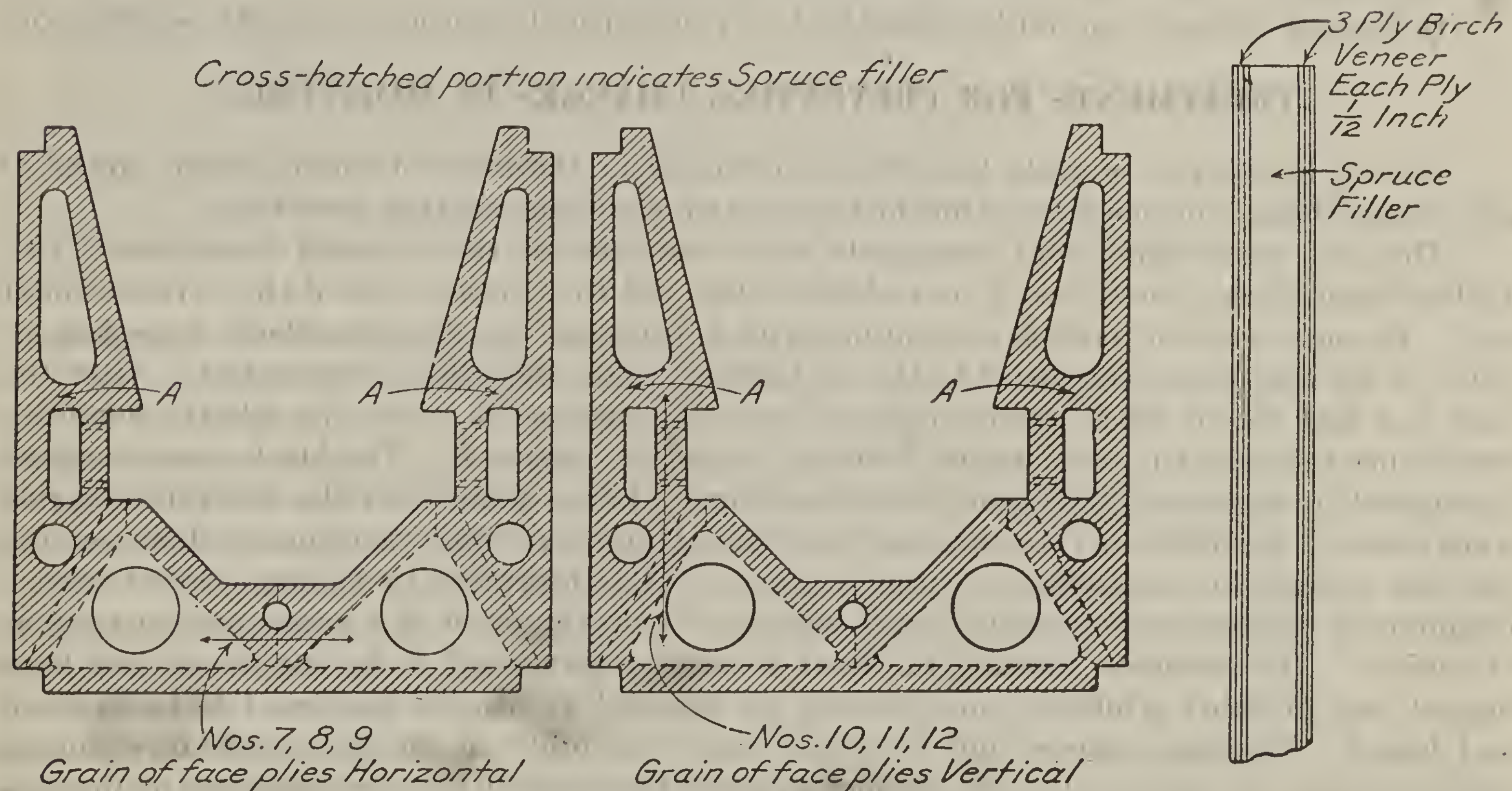

Fig. 76.—Engine bearers, spruce-filler type.

It is to be noted that the spruce-filler type was somewhat superior to the other in thrust loading and much superior in vertical loading; also that the bearers of the former type with the face grain of the plywood vertical were superior to those with the face grain horizontal. It may be mentioned that these particular bearers were designed to take vertical loading only.

TESTS ON BAKELIZED CANVAS (MICARTA).

In connection with tests on substitutes for wood in aircraft construction several series of tests were made upon micarta members. Reference has already been made to tests upon spruce struts covered with micarta. Tests were also made on hollow longerons of micarta and on a few samples of micarta wing spars.

Several tubes of micarta were submitted for test as substitutes for wood in longerons. These tubes were hollow, 36 inches long, 1 inch square outside, and made up of 6 plies of canvas, the walls being about one-eighth inch thick. For comparison a number of spruce sticks 1 inch square and 36 inches long were cut from a plank selected at random and comparative tests made upon the tubes and sticks. The tests show the following properties, compared to spruce (moisture about 10 per cent):

1. Modulus of elasticity about two-thirds that of spruce.
2. Fiber stress at elastic limit in bending about four-fifths that of spruce.
3. Tensile strength half that of spruce.
4. Specific gravity three times that of spruce.
5. Compression parallel to the grain, elastic limit, one-half that of spruce.
6. Compression parallel to the grain, maximum load, three times that of spruce.

Impact tests upon several longerons and impact tests made upon several samples of I-beam and hollow section wing spars of micarta indicate that this material is superior to average spruce (about 10 per cent moisture) in the following properties: (*a*) Fiber stress at the elastic limit in impact; (*b*) elastic resilience in impact (much superior).

The cause of the much greater elastic resilience lies not only in the higher fiber stress at the elastic limit but also in the lower modulus of elasticity in impact.

In general, micarta can not be considered as a substitute for spruce in aircraft construction.

TREATMENTS FOR PREVENTING CHANGES IN MOISTURE.

Several long series of tests have been conducted in the hope of finding some means of preventing changes of moisture in finished parts with changing weather conditions.

The first series had to do principally with varnishes of the so-called waterproof type. Yellow birch blocks were given a coat of silex filler and then three coats of the varnish under test. In some cases the varnish was applied with a brush and in others the blocks were dipped. Some of the specimens were dried in the air between coats and others were baked. After the final coat had set the blocks were hung in a humidity chamber in which the relative humidity was 95 per cent and the temperature between 75 and 80 degrees F. The blocks were weighed at intervals to determine the absorption of moisture. It was found that the absorption varied widely among the different varnishes and that baking improved some varnishes while increasing the rate of moisture transmission through others. The absorption in 17 days varied from a minimum of 4.36 grams per square foot of surface to a maximum of 26.8 grams per square foot of surface. The specimen showing the least absorption happened to be one which had been dipped and air dried, while the one showing the greatest absorption happened to be brushed and baked. The tests showed not only the great variability in moisture resistance among good varnishes but showed also that the moisture resistance was in all cases increased by increasing the number of coats of varnish applied. Table 25 shows the absorption of water by specimens given various miscellaneous treatments. The absorptions at 17 days are comparable with the figures just quoted. None of the treatments furnished the desired water resistance.

TABLE 25.—*Humidity tests of miscellaneous treatments.*

Wood, yellow birch: Average thickness, 0.6 inch; average width, 4 inches; average length, 8 inches; average surface area, 0.54 square foot; average weight, 0.49 pound air dry; average volume, 0.011 cubic foot.

Treatment.	Number of specimens averaged.	Average absorption in grams per square foot of surface in— 3 days.	10 days.	17 days.
1. Muslin glued with Le Page's Cold Glue, 4 coats of airplane dope, and 2 coats of airplane gray enamel	2	1.85	4.36	7.39
2. Three brush coats of orange shellac	2	1.68	4.49	7.98
3. Paste filler (silex), 1 coat airplane gray undercoat, 3 coats airplane gray enamel (Adams & Elting Co.)	2	1.80	4.79	8.23
4. Paste filler (silex), 2 brush coats orange shellac, 2 brush coats Lowe Bros. Finishing Varnish V 801	2	1.43	5.36	8.30
5. Paste filler (silex), 2 coats of Hampden's W. P. Varnish No. 1 and 1 coat of Lowe Bros. Marine Spar	2	1.55	5.11	8.35
6. Paste filler, 2 coats of white lead, linseed oil, and lampblack, 1 coat of rubbing varnish, 4 coats of spar varnish	5	2.60	6.21	10.23
7. Two brush coats of orange shellac and 2 brush coats of Lowe Bros. Finishing Varnish V 801	2	1.97	6.75	10.36
8. Two brush coats of orange shellac and 3 brush coats of Lowe Bros. Finishing Varnish V 801	2	2.22	5.79	9.93
9. Wood dyed alternating the two following solutions: No. 1—100 gr. aniline hydrochloride, 40 gr. ammonium chloride, 650 gr. water. No. 2—100 gr. copper sulphate, 50 gr. potassium chlorate, 615 gr. water; washed with soap and water and thoroughly rubbed with vaseline; 3 coats of Lowe Bros. Marine Spar Varnish were added	2	4.20	10.31	15.44
10. Four brush coats of Toch Bros. 1017 Marine Varnish thinned with turpentine	2	3.56	11.90	17.88
11. One-half hour vacuum and 1 hour atmospheric pressure (Special Varnish, Adams & Elting Co.)	1	4.86	13.40	20.7
12. One-half hour vacuum and 1 hour atmospheric pressure (Toch Bros. No. 1017 M. S. Preservative	2	6.04	16.72	25.4
13. Hot and cold treatment with paraffin dissolved in gasoline	2	6.55	23.9	....
14. Five applications of hot boiled linseed oil and 2 coats of prepared wax, each coat applied at intervals of not less than 4 hours and each thoroughly rubbed	2	14.0	36.7	47.6
15. Same as 9 except that no varnish was applied	1	21.6	....	....
16. Plain yellow birch panels, no treatment	10	20.5	42.5	51.9

Some conclusions not already mentioned follow:

(1) A more effective coating may be secured by dipping than by hand brushing.

(2) Cellulose varnishes are not as durable as oil varnishes.

(3) Linseed oil and wax treatments are not effective in keeping out moisture.

(4) All the varnishes tested were somewhat affected by water, including those that do not turn white as well as those which do.

(5) Very resistant coatings may be secured by using certain rubbing varnishes followed by top coats of spar varnish as a protection, also by using certain linseed oil varnishes, covered by a more durable China wood oil varnish.

Tests were also conducted on electroplated metal coatings and on vulcanized rubber coatings. Both of these types of coating are extremely resistant to the penetration of moisture, so long as they remain intact. The metal coating in particular, however, is rather delicate and does not adhere to the wood. The vulcanized rubber coatings were about an eighth of an inch thick and would probably be quite satisfactory from the standpoint of durability.

Of all the coatings upon which experiments were made, an aluminum leaf coating appears to be the most satisfactory from the standpoint of resistance to moisture penetration combined with general feasibility. This coating consists, in effect, of aluminum leaf laid over the

surface between layers of varnish, just as sign painters lay on leaf over size. The leaf itself has no wearing strength and the coating has just the durability and wear resistance of the coats of varnish and enamel placed over the leaf. The resistance of the leaf coating to the passage of moisture is very remarkable indeed, as will be seen from a study of table 26 and figure 81, which present comparable data on several kinds of aluminum leaf coatings and several common kinds of finish.

TABLE 26.—*Humidity tests of metal leaf coatings.*

Treatment.	Number of specimens averaged.[1]	Average absorption in grams per square foot of surface for—				
		3 days.	10 days.	17 days.	24 days.	31 days.
Silex filler, gold size, aluminum leaf, and 3 coats of E. P. black lacquer	2	−0. 210	0. 084	0. 168	−0. 042	0. 461
Silex filler, 1 coat of rubbing varnish, gold size, imitation gold leaf, 1 coat Valspar	3	0. 218	0. 445	0. 805	....	....
Silex filler, 1 coat of rubbing varnish, gold size, aluminum leaf, 1 coat Valspar	1	0	0. 252	0. 420	....	....
Silex filler, 3 brush coats Hampden's waterproof varnish No. 2	10	1. 28	4. 56	7. 29	....	....
5 applications of linseed oil applied hot and 2 coats of wax	2	14. 0	36. 7	47. 6	....	....
No treatment	10	20. 5	42. 5	51. 9	....	....

[1]*Average data on yellow birch panels.*

Thickness	inch	0. 60
Width	inches	3. 960
Length	do	8. 000
Surface	square feet	. 540
Weight (air-dry)	pound	. 490
Volume	cubic feet	. 011

It has been found, in actual practice, that the process is entirely workable, and very good results have already been secured from its use.

The following instructions explain in detail the method of applying aluminum leaf to propellers. The same method could be used in coating other aircraft parts if it were found desirable to do so.

INSTRUCTIONS FOR APPLYING ALUMINUM LEAF TO AIRCRAFT PROPELLERS.

The leaf used in this process is exceedingly thin and light, there being probably 12,000 to 15,000 leaves per inch which makes it appear difficult to handle. If the instructions are carefully followed, however, the leaf may be easily and thoroughly applied.

Preparation.—It is important to provide a perfectly smooth surface over which to apply the coating. The surface should be sanded perfectly smooth and be free from all tool marks or other imperfections. The bolt holes at the hub should be plugged with corks which should be cut off flush and finished in the same manner as the rest of the surface.

Filling.—For open-grained woods a coat of filler consisting of 83 per cent liquid and 17 per cent silex should be used. The liquid should consist of 77 per cent airplane spar varnish and 23 per cent turpentine. The silex should pass a 200-mesh sieve.

The filler should be applied to the wood and allowed to flatten, after which it should be rubbed off across the grain so as to thoroughly fill the pores. The filler should dry at least 24 hours, after which it should be sanded lightly.

Shellac varnish undercoating.—The shellac varnish should consist of four and one-half pounds of orange shellac gum in one gallon of clean, neutral, denatured alcohol.

This varnish should be applied evenly over the surface of the propeller and allowed to dry three or four hours, after which it should be sanded lightly.

Size.—The size should consist of 75 per cent airplane spar varnish and 25 per cent turpentine. It is suggested that a small amount of Prussian blue in Japan be added to the varnish to give it a color, so that spots subsequently left uncovered by the leaf will be readily visible.

This size should be brushed evenly over the surface as sparingly as possible and allowed to dry until a tack is reached, which will permit the handling of the propeller immediately after the application of the leaf. The time will vary with the varnish and the kind of a day. The varnish should probably dry an hour and a half on a light dry day or in a heated building in the winter time, but a longer time may be required on cloudy or damp days. This is a very important point and should be carefully considered as the coating hardens very slowly after the leaf is applied.

Care should be exercised so as not to produce fatty edges or runs in applying the size. If they occur, the leaf will be easily rubbed from the surface in handling the blade.

It has been found convenient to size one side of the blade at a time; that is, the front or back of the blade. This is a convenience in applying the leaf later.

Aluminum leaf.—After the size has reached the right tack the leaf should be applied very rapidly over the surface, and after the sized surface has been entirely covered the leaf should be patted down with the palm of the hand or with a pad of cotton, after which the rough edges should be rubbed away (see fig. 79b). Any points not covered with leaf should be coated by applying a small piece of leaf to the spot with the fingers. The coating should be rubbed well with a piece of cotton which has been dipped in aluminum powder. This will insure the leaf sticking securely over the entire surface and will fill any small holes not already filled.

Aluminum leaf comes in packs containing 500 leaves. The pack is divided up into 10 or 20 books containing 50 or 25 leaves, respectively. The metal leaf is placed between the pages of these books and comes in 4-inch, 4½-inch, 5-inch, or 5½-inch squares.

It has been found best to apply the leaf directly from the book by turning back the first page of the book halfway, holding the same between the first and second fingers of the right hand (see fig. 78a). The book itself should be held between the thumb and fingers and in such a way that the back of the hand will be toward the work when the leaf is applied, the book being given a slight bend to prevent the corners of the leaf from drooping. The end of the leaf exposed by turning back the first page of the book should be placed against the surface to be coated and held securely in place by the left hand (see fig. 78b). The sheet held between the first and second fingers should be drawn back so as to allow the whole leaf to come in contact with the surface (see fig. 79a). The next sheet should be applied in a like manner, lapping edges with the first, and so on. The best results will be obtained if the gilder works in one direction with each row of leaf; that is, from left to right. If this be done, it will aid considerably in completing and smoothing off the surface.

It is suggested that in turning the pages of the books the back of the book be held between the first two fingers of the left hand (see fig. 77a). The leaves from which the leaf has been removed should be turned back and held between the thumb and first finger of the left hand. The next sheet of paper may then be turned back exposing one-half of the next leaf. The operation of changing the book from left to right hand is shown in figure 77b.

Large hub hole.—The large hub hole should receive the same treatment as the rest of the propeller. In applying the leaf to the hub hole it has been found convenient to cut the books

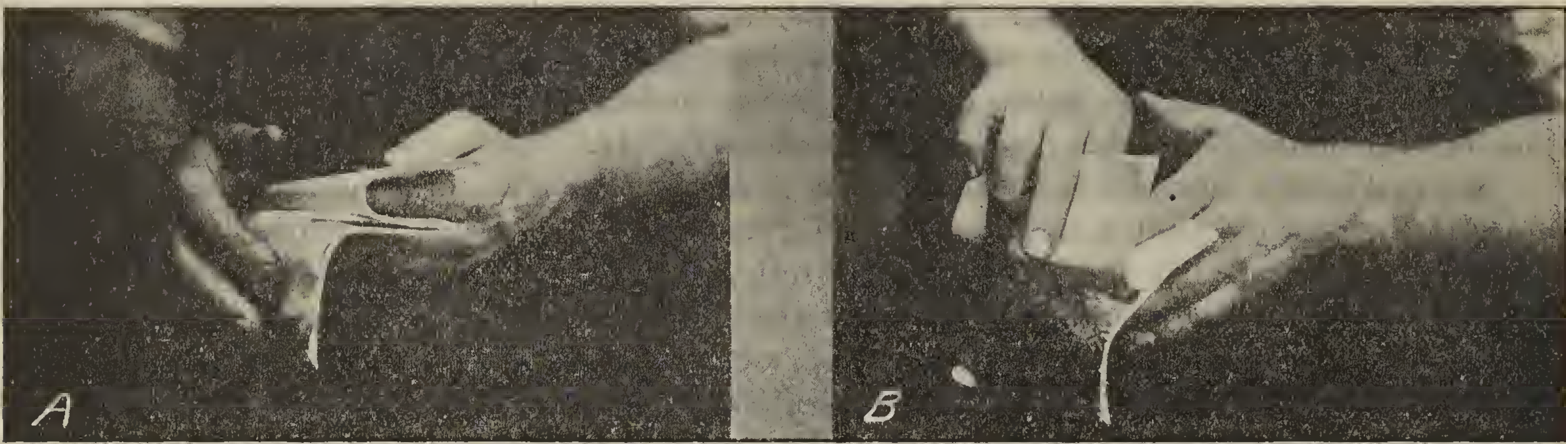

Fig. 77.—Aluminum leaf coating. (a) Method used in turning page of book. (b) Transferring book from left to right hand.

Fig. 78.—Aluminum leaf coating. (a) Method of holding book when applying leaf. (b) First operation in laying leaf.

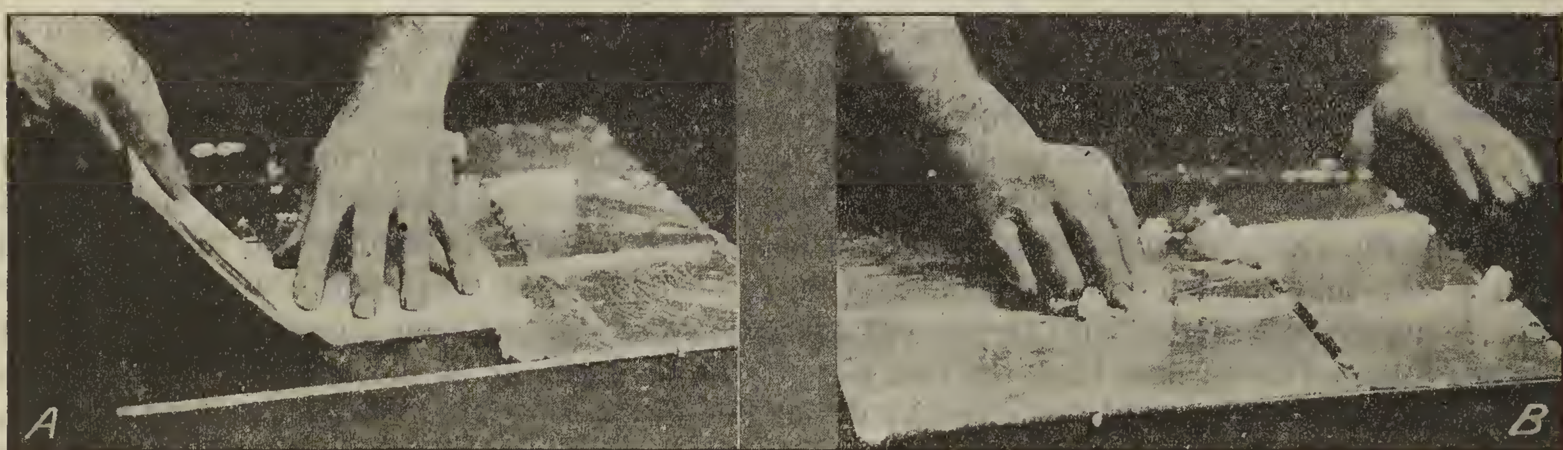

Fig. 79.—Aluminum leaf coating. (a) Second operation in laying leaf. (b) Smoothing off surface after application of leaf.

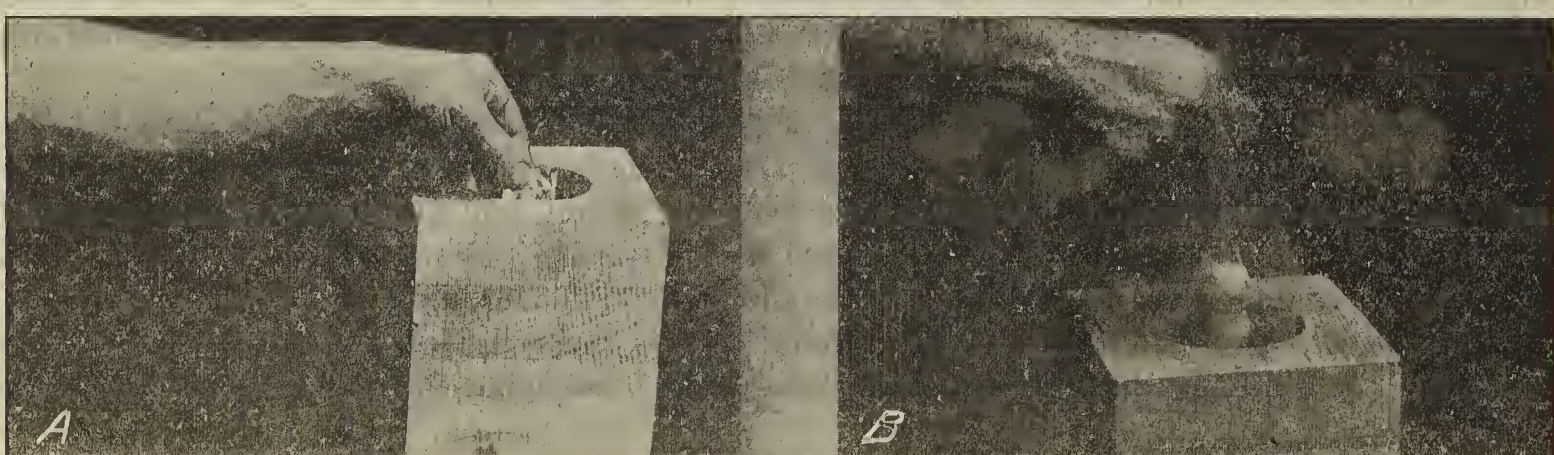

Fig. 80.—Aluminum leaf coating. (a) Applying leaf to large hub hole. (b) Smoothing off leaf in large hub hole.

of leaf up into about 1-inch strips of leaf and paper and drop them vertically into the opening and bring into contact with the size (see fig. 80a). After the entire surface of the hole has been covered the leaf should be patted into place with a wad of cotton attached to the end of a stick (see fig. 80b).

Small hub holes.—These holes should be simply corked up with ordinary corks, the tops of which should be cut off flush with the surface of the propeller and covered with the regular finish.

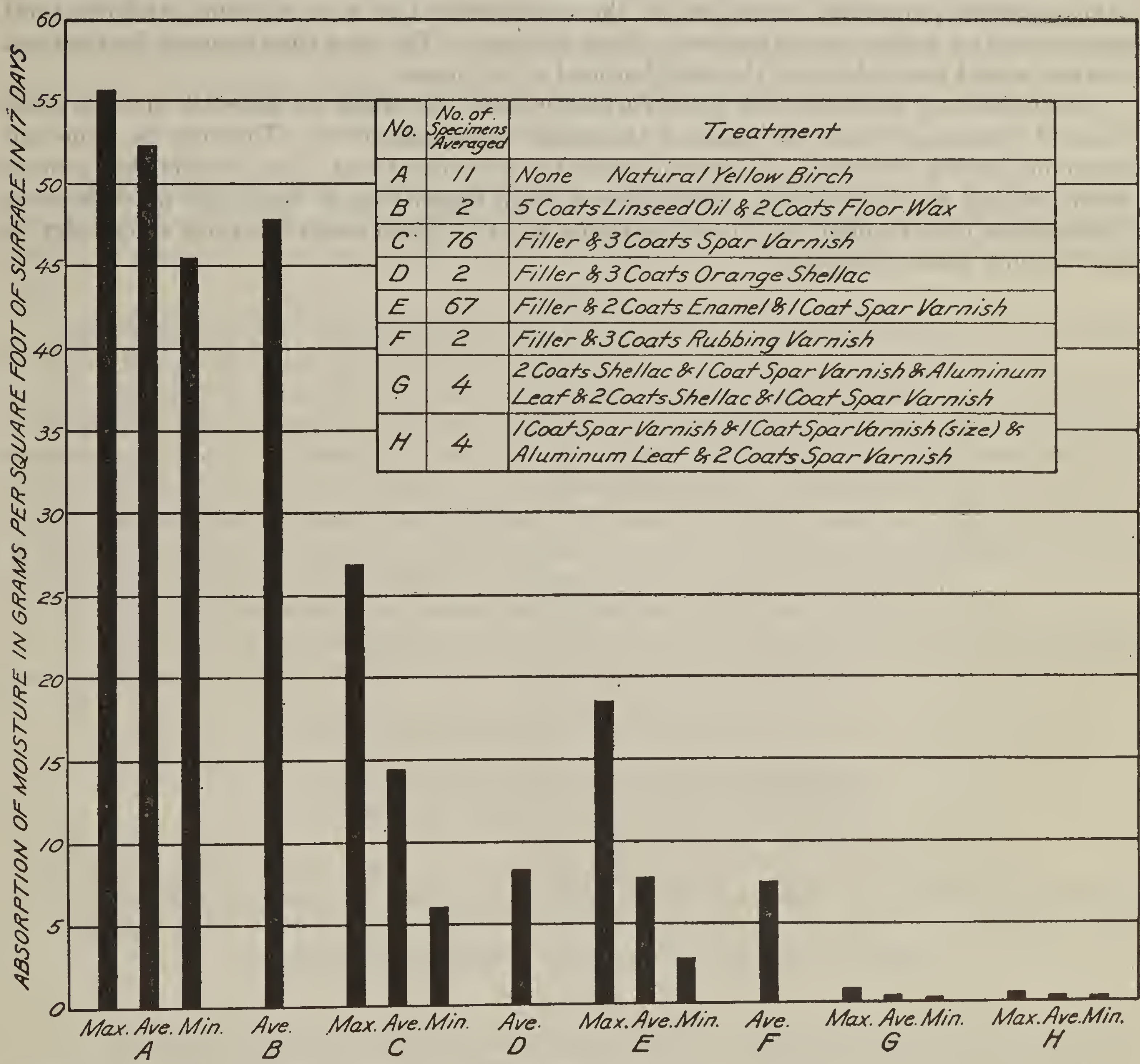

Fig. 81.—The comparative effectiveness of various coatings in moisture-proofing wood. Humidity of air during tests, 95 to 100 per cent.

Shellac color varnish.—After the application of the leaf two coats of shellac color varnish should be applied. This varnish should be made as described under the heading of "Shellac varnish undercoat," except that enough color should be added to produce a mahogany color. Four or 5 per cent of Bismark brown in the shellac varnish gives about the right color. The amount of this material to get the best results should be determined by trial. The varnish should dry three or four hours before rubbing or recoating.

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Each coat of shellac should be rubbed down lightly between coats without the use of oil.

Finishing varnish.—A final flowing coat of airplane spar varnish should be applied and allowed to dry about 48 hours. This coating should not be rubbed or sanded.

Estimated time required to coat a propeller.—The time required to apply the leaf to a propeller should not be more than 40 or 50 minutes. This time could be reduced after the finisher becomes more experienced. The estimated time required for applying the complete finish described in the foregoing paragraphs would be in the neighborhood of 8 or 10 hours, and the total time required for drying the various coats about 90 hours. The total time required for the total operation would probably be in the neighborhood of 100 hours.

Modification of aluminum leaf spirit varnish process.—It might be desirable in some cases to use oil varnishes or enamels in lieu of the shellac described above. This may be done and satisfactory results obtained. In case oil varnishes are substituted, it is possible that a more durable coating will be obtained. It requires a much longer time to apply the finish because of the greater time required for the oil varnishes to dry. Each coat of varnish should dry at least 72 hours before recoating.

APPENDIX.

For convenient reference, specifications for the determination of the moisture content in wood and for the determination of the specific gravity of wood are embodied in the appendix.

THE DETERMINATION OF MOISTURE CONTENT IN WOOD.

SELECTION OF TEST SPECIMENS.

1. Short pieces of wood dry out much more rapidly than longer ones. In order to reduce the time required for drying, the length of the test specimen in the direction of the grain should usually be about 1 inch or not more than enough to give a volume of from 5 to 25 cubic inches.

TESTS.

2. Having selected a representative piece of material for a test specimen, the procedure for determining the moisture content is as follows:

3. Immediately after sawing remove all loose splinters and weigh the test specimen. It is important that the weight be taken immediately after sawing, since the wood is subject to moisture changes on exposure to the air. The degree and rapidity of change are dependent on the moisture content of the piece and the conditions of the air to which it is exposed.

4. Put the test specimen into a drying oven and dry at approximately 212° F. (100° C.) to constant weight. This usually requires three to five days. Specimens placed in the oven for drying must be open piled to allow free access of air to all parts of each piece.

5. Weigh the test specimens immediately after removing from the oven.

6. The loss in weight expressed in per cent of the dry weight is the percentage moisture content of the wood from which the test specimen was cut.

$$\text{Percentage moisture} = \frac{(W-D)}{D} \times 100$$

W = original weight as found under paragraph 3.
D = oven-dry weight as found under paragraph 5.

ACCURACY.

7. In order to insure good results, the weight should be correct to within at least one-half of 1 per cent.

THE DETERMINATION OF SPECIFIC GRAVITY OF WOOD.

GENERAL.

1. The specific gravity (or density) of all woods used in aircraft construction shall be determined, when required, in accordance with this specification. Method A shall be used whenever possible.

SELECTION OF TEST SPECIMENS.

2. Short pieces of wood dry out much more rapidly than longer ones. In order to reduce the time required for drying, the length of the test specimen in the direction of the grain should usually be about 3 centimeters.

METHOD A.

3. Having selected a representative piece of material for a test specimen, the procedure is as follows:

4. Immediately after sawing remove all loose splinters and put the test specimen into a drying oven and dry at about 212° F. (100° C.) to constant weight. This usually requires three to five days. Specimens placed in the oven for drying must be open piled to allow free access of air to all parts of each piece.

5. Weigh the test specimen.

6. Determine the volume of the oven-dry specimen preferably by the method described in paragraphs 9 to 12.

7. Specific gravity $=\frac{M}{V}$

M = oven-dry weight in grams as determined under paragraphs 4 and 5.

V = oven-dry volume in cubic centimeters as determined under paragraph 6.

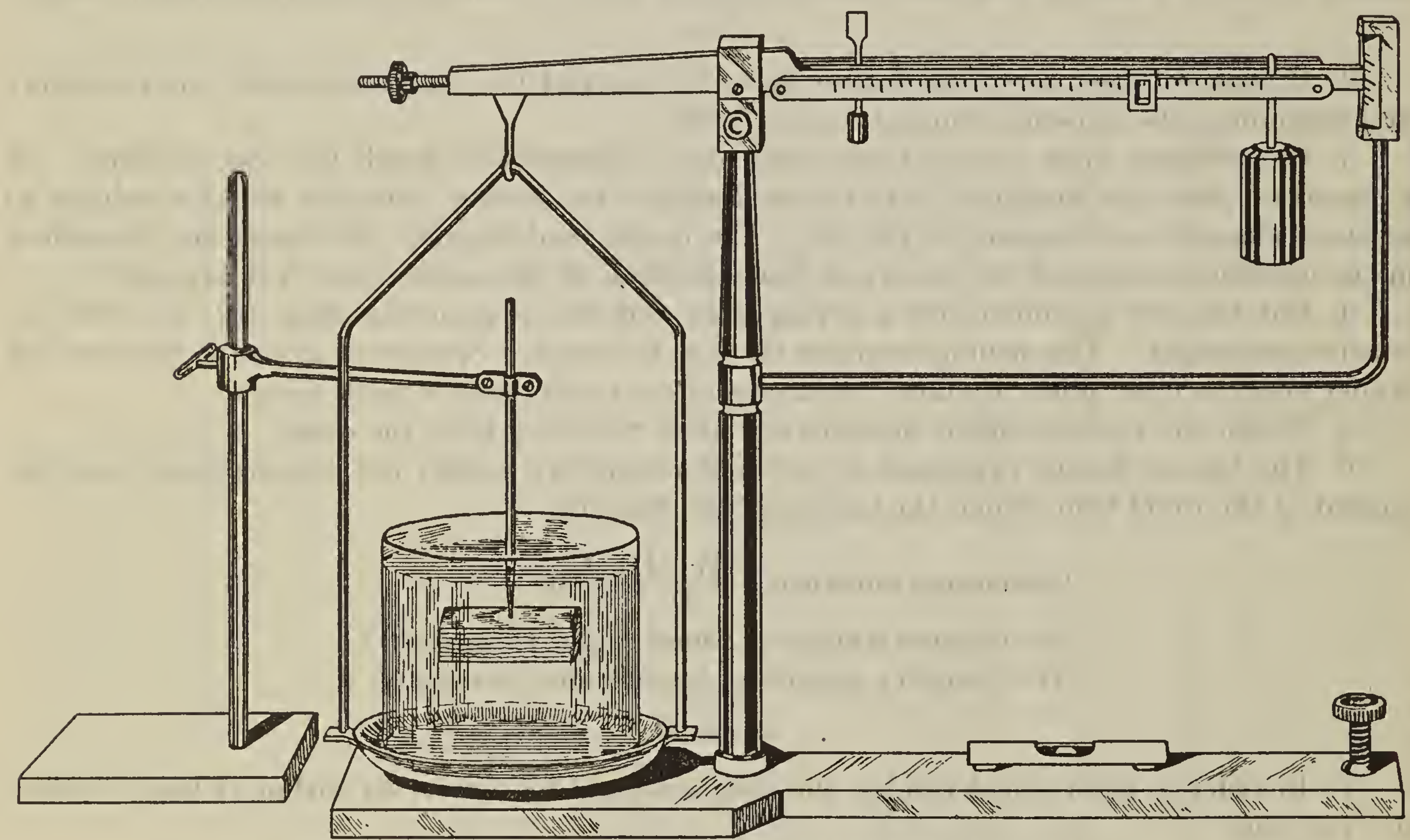

Fig. 82.—Determination of specific gravity of wood.

REDUCTION FACTORS.

8. One inch = 2.54 centimeters; 1 ounce = 28.4 grams; 1 cubic inch = 16.4 cubic centimeters; 1 pound = 454 grams.

DETERMINATION OF VOLUME.

9. After the oven-dry weight has been obtained dip the test specimen in hot paraffin and allow it to cool. Scrape off any surplus paraffin which adheres to the specimen.

10. The volume of the test specimen is found by determining the weight of water it displaces when immersed, as shown in figure 82. This weight in grams is numerically equal to the volume of the specimen in cubic centimeters.

11. It is important that the determination of the volume by weighing be made as quickly as possible after the immersion of the specimen, since any absorption of water by the specimen directly influences the accuracy of the result. By estimating the volume of the specimen and placing approximately the required weights on the plan before the specimen is immersed the time necessary for balancing may be reduced to a minimum.

12. To determine the volume, a container holding sufficient water for the complete submergence of the specimen is placed on one pan of a balance scale. The container and water are then balanced with weights added to the other scale pan. By means of a sharp-pointed rod, shown in figure 82, the specimen is held completely submerged and not touching the container while the scales are again balanced. The weight required to balance is the weight of water displaced by the specimen, and, if in grams, is numerically equal to the volume of the specimen in cubic centimeters.

13. The sharp-pointed rod, by means of which the specimen is held in position, should be of as small diameter as possible. Care should be taken not to lower the specimen into the water to a much greater depth than required to completely submerge it; otherwise the weight of water displaced by the rod will affect the accuracy of the result.

ACCURACY.

14. In order to insure good results, the weights and volumes should be correct to within at least one-half of 1 per cent.

METHOD B.

15. The following method of determining the specific gravity may be used when the apparatus required by test A is not available.

16. Select the test specimen as in paragraph 2.

17. Dry the specimen as in paragraph 4.

18. Cut the oven-dried specimen while hot to a standard volume of not less than 80 cubic centimeters so that its volume may be accurately determined by measurement.

19. Weigh the oven-dried specimen while hot and record its weight in grams. This weight must be accurate to within one-half of 1 per cent.

20. Determine the volume in cubic centimeters of the oven-dried specimen while hot by measuring each edge in centimeters and taking measurements to the nearest one-half millimeter.

20. Specific gravity $=\frac{M}{V}=\frac{\text{weight in grams}}{\text{volume in cc}}$.

WASHINGTON : GOVERNMENT PRINTING OFFICE : 1919